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UNSTEADY FLOW DISTORTION PAST BLADES: SOURCES OF NOISE GENERATION IN ROTATING FLOWS

ONR GRANT N00014-89-J-1799
WORK UNIT NO. 432 U 001

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Performance (Technical) Report, December, 1991, on ONR Grant N00014-89-J-1799

UNSTEADY FLOW DISTORTION PAST BLADES:

TABLE OF CONTENTS

Page

- OBJECTIVES 3
- RESEARCH PLAN 4
- PRINCIPAL PHYSICAL AND THEORETICAL CONCEPTS 5
- EXPERIMENTAL TECHNIQUES 8
- GENERIC CLASSES OF EDGE/SURFACE INTERACTION 11
  - √ LEADING-EDGE
  - √ TRAILING-EDGE
  - √ LEADING-/TRAILING-EDGE
- EXPERIMENTAL SYSTEMS 15
  - √ GENERIC SYSTEMS FOR LEADING- AND TRAILING-EDGE INTERACTIONS
  - √ ACTIVELY-CONTROLLED PUMPING SYSTEM
- FLOW STRUCTURE IN ACTIVELY-CONTROLLED RADIAL-FLOW MACHINE 36
  - √ OVERALL SYSTEM RESPONSE
  - √ FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER
  - √ FLOW STRUCTURE AND PRESSURE SOURCES ALONG DIFFUSER BLADE OR CUTOFF
  - √ FLOW STRUCTURE AND PRESSURE SOURCES AT TRAILING-EDGE OF IMPELLER BLADE
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UNSTEADY FLOW DISTORTION PAST BLADES: OBJECTIVES

GENERAL

- DETERMINE FLOW STRUCTURE AT LEADING- AND TRAILING-EDGES OF BLADING IN TERMS OF VELOCITY GRADIENTS REPRESENTING PRESSURE SOURCES.
- EMPLOY ACTIVE AND PASSIVE CONTROL TECHNIQUES TO MANIPULATE CRUCIAL PHASE SHIFTS OF VORTICITY FIELDS PAST BLADING.

DESIGN AND IMPLEMENTATION OF EXPERIMENTAL SYSTEMS

- GENERIC, CONTROLLED SYSTEMS FOR STUDY OF BASIC CLASSES OF LEADING- AND TRAILING-EDGE INTERACTIONS.
- UNIQUE RADIAL FLOW MACHINE FOR SIMULTANEOUS ACTIVE CONTROL AND FLOW VISUALIZATION.

DEVELOPMENT OF EXPERIMENTAL TECHNIQUES

- TECHNIQUES FOR QUANTITATIVE BUBBLE AND PARTICLE TRACKING VIA LASER DIAGNOSTICS.
- METHODS OF EVALUATION OF IMAGES VIA LASER INTERROGATION.
- APPROACHES TO TWO- AND THREE-DIMENSIONAL IMAGE CONSTRUCTION.

UNSTEADY FLOW DISTORTION PAST BLADES: RESEARCH PLAN

PHASE I

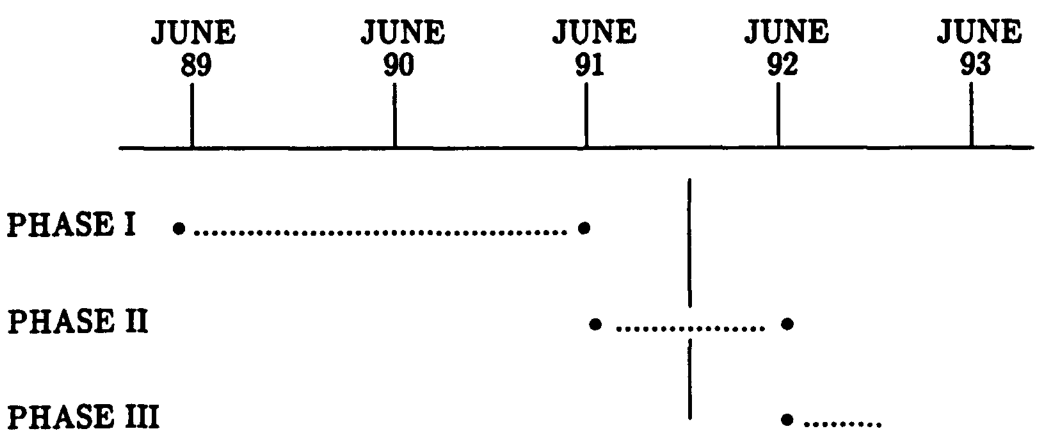
- DESIGN, CONSTRUCTION AND DEVELOPMENT OF:
  - √ UNIQUE ROTATING MACHINE FOR VISUAL ACCESS AND ACTIVE CONTROL
  - √ CONTROLLER SYSTEMS FOR ROTATING MACHINE
  - √ LASER DIAGNOSTIC TECHNIQUES FOR QUANTITATIVE FLOW VISUALIZATION AND INTERPRETATION
- EXPERIMENTAL STUDY OF GENERIC CLASSES OF LEADING-/TRAILING-EDGE INTERACTIONS

PHASE II

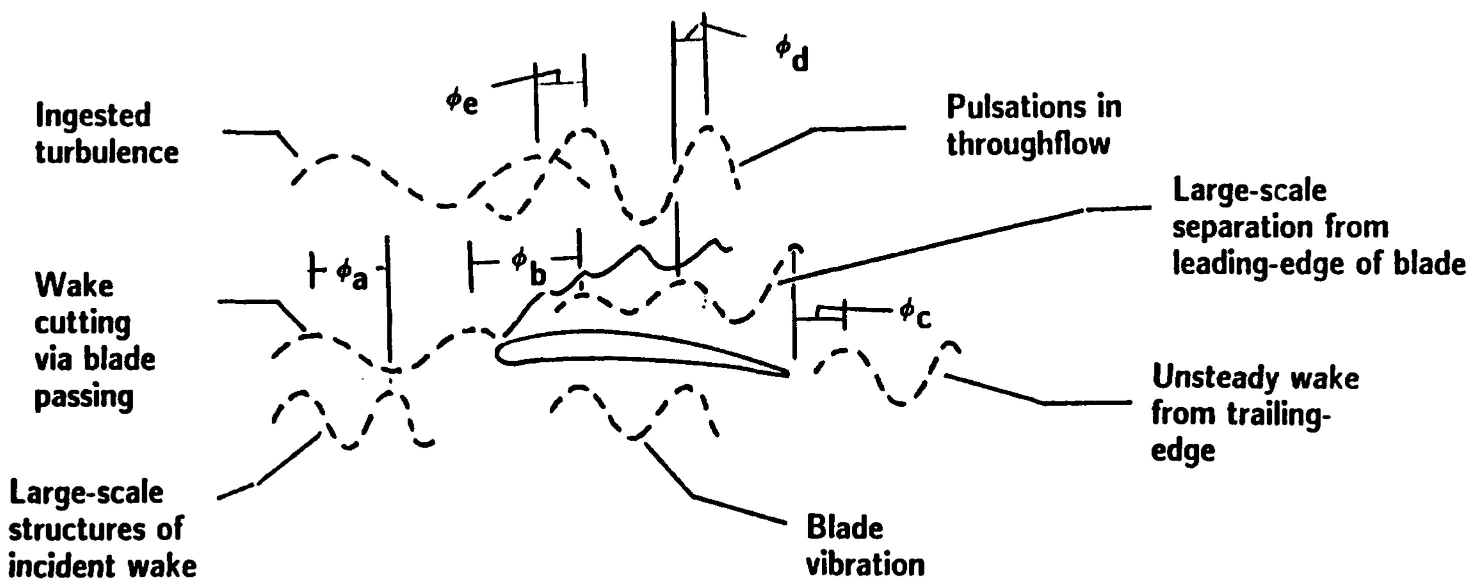
- PRELIMINARY STUDIES OF FLOW STRUCTURE IN ROTATING MACHINE VIA LASER DIAGNOSTICS
- ACTIVE/PASSIVE CONTROL CONCEPTS OF GENERIC EDGE INTERACTIONS

PHASE III

- ACTIVE CONTROL STUDIES OF FLOW IN ROTATING MACHINE
- CONTROL OF GENERIC EDGE INTERACTIONS



PRINCIPAL PHYSICAL CONCEPTS



The principal features of this research program involve identification of the elements of unsteady flow structure and their active control by applying disturbances of desired frequency and phase. Proper phase shift ϕ between dynamic events may allow attenuation of unsteady mechanisms of noise generation.

PRINCIPAL MECHANISMS OF FLOW DISTORTION RELATED TO NOISE GENERATION: CONCEPTS

I. INTERPRETATIONS OF PRESSURE SOURCE TERMS

$$\nabla^2 p = 2\rho \left\{ \frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x} \right\}$$

$$= -\rho \left\{ \nabla \cdot (\underline{\omega} \wedge \underline{V}) + \nabla^2 \left(\tfrac{1}{2} V^2\right) \right\}$$

$$= -\rho \left\{ \frac{\partial^2 v_i v_j}{\partial x_i \partial x_j} \right\} \qquad T_{ij} \simeq \rho_o v_i v_j$$

II. FAR-FIELD ACOUSTIC PRESSURE DUE TO FLOW DISTORTION IN FREE SPACE

Expressions of (I) serve as source terms in inhomogeneous wave equations. Solve for far-field density or pressure.

III. FAR-FIELD ACOUSTIC PRESSURE DUE TO FLOW DISTORTION ADJACENT TO SURFACE/BODY

(a) $p(\underline{x},t)$ via Lighthill's T_{ij} using deductive theory of surface effects.

(b) $p(\underline{x},t) = \dfrac{-x_i}{4\pi c|\underline{x}|^2}\dfrac{\partial}{\partial t} F_i$ (Curle, 1955)

$$F_i = \int \rho_o \underline{\nabla} X_i(y) \cdot (\underline{\omega} \wedge \underline{V})\left(\underline{y}, t - \frac{|\underline{x}|}{c}\right) d^3\underline{y} \qquad \text{(Howe, 1989)}$$

$$\underline{F} = -\sigma \rho_o \frac{\partial}{\partial t} \int (\underline{x} \wedge \underline{\omega}) d^3\underline{x} \qquad \text{(Lighthill, 1986)}$$

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PARTICLE IMAGE VELOCIMETRY (PIV) VIA LASER DIAGNOSTIC METHODS

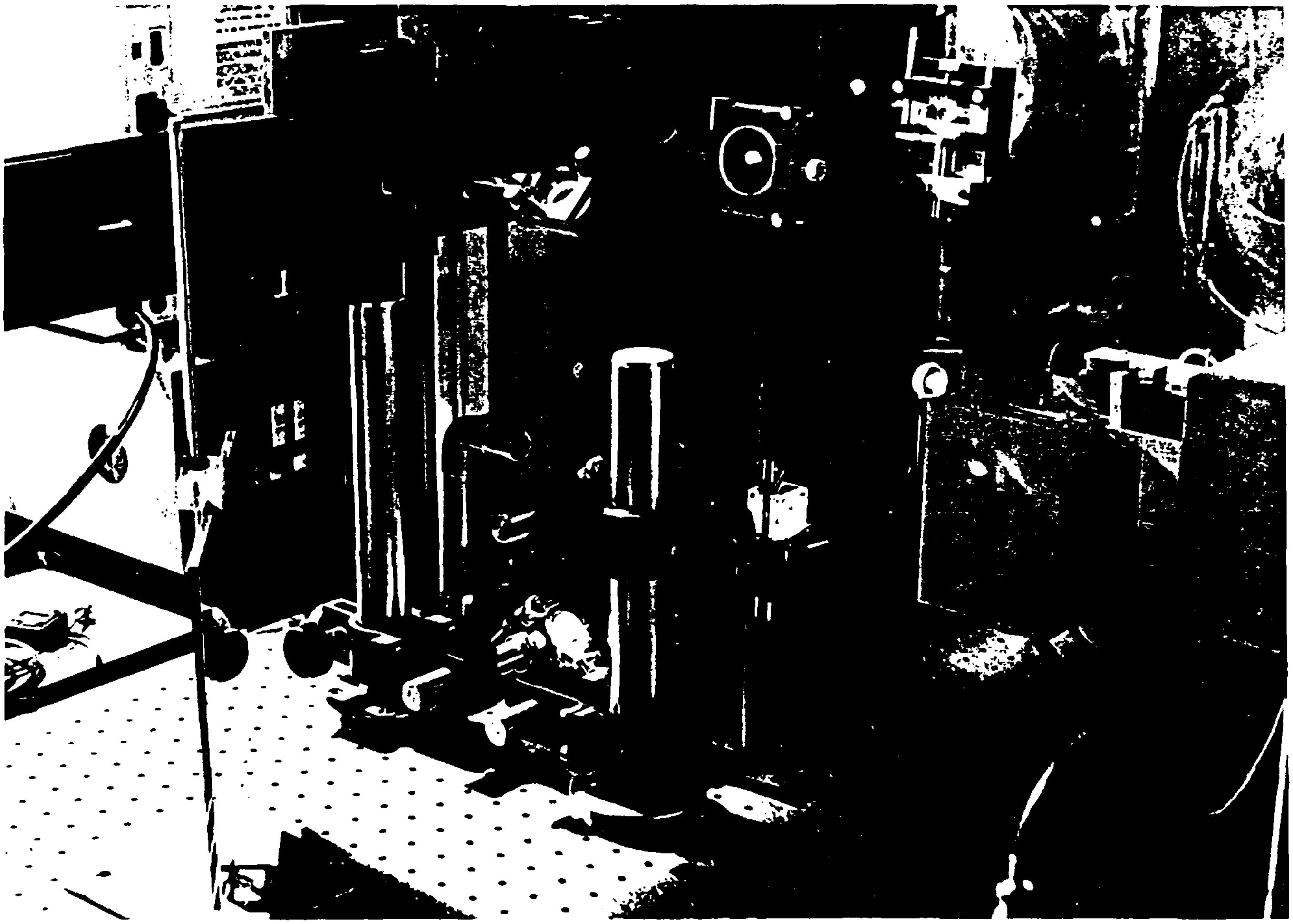
GOALS

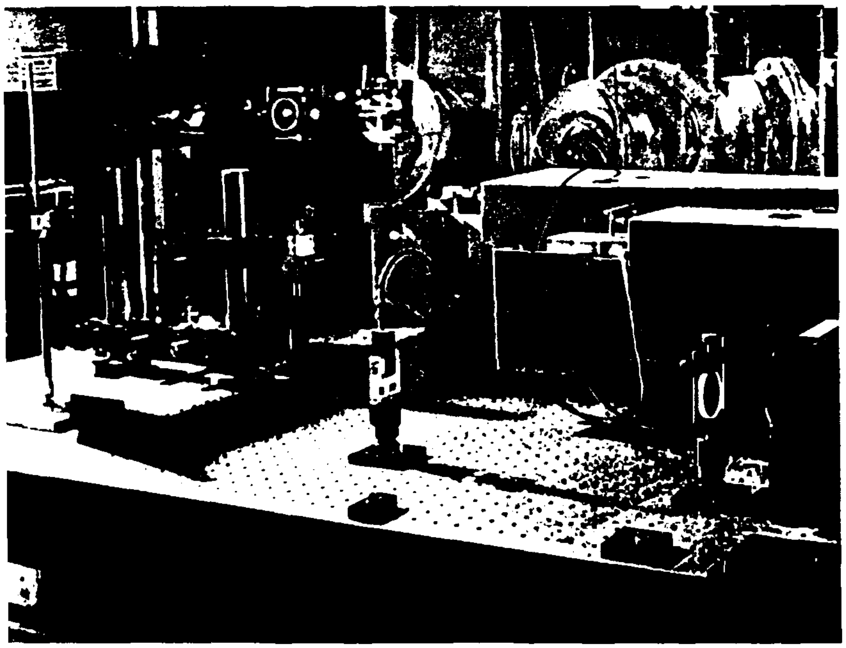
- INSTANTANEOUS VELOCTY FIELD ACROSS PLANE OF FLOW AT ARBITRARY PHASE OF ROTATING BLADE SYSTEM
- HIGH RESOLUTION MEASUREMENTS VIA SMALL PARTICLE DISPLACEMENTS ($\sim 10^2$ μm) AND MINIMAL INTERPOLATION.
- CHARACTERIZATION OF VELOCITY GRADIENTS REQUIRED FOR CALCULATION OF VORTICITY AND PRESSURE SOURCES

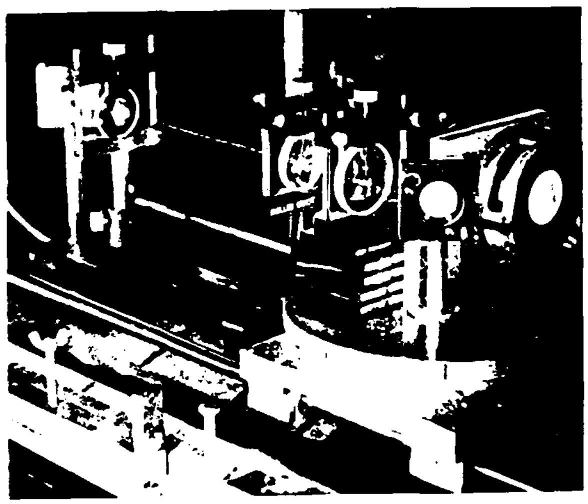
SYSTEM DEVELOPMENT

- MINIMIZATION OF PARTICLE SIZE AND OPTIMIZATION OF IMAGE FOCUSING VIA PROPER COMBINATION OF LASER SOURCE, CAMERA, LENS SYSTEM
- IMAGE SHIFTING VIA OSCILLATING BIAS MIRROR
  - √ PRECLUDE DIRECTIONAL AMBIGUITY
  - √ OPTIMIZE PARTICLE DISPLACEMENT AND FRINGE SPACING
- GENERATION OF HIGH-INTENSITY PULSED- AND SCANNED-LASER SHEETS
  - √ DUAL-PULSED YAG SYSTEM WITH BEAM COMBINER OPTICS
  - √ SINGLE CW SCANNED ARGON-ION SYSTEMS (ACOUSTO-OPTIC AND MIRROR SCANNER)
- OPTICAL SYSTEMS FOR TRANSLATION AND ROTATION OF LASER SHEETS
- INTEGRATED COMPUTER CONTROL OF
  - √ LASER FIRING
  - √ IMAGE SHIFTING
  - √ PUMP IMPELLER ROTATION
  - √ CAMERA TRIGGERING
  - √ PUMP INLET FLOW
  - √ EXTERNAL SHUTTERS
- HARDWARE INTERFACING AND SOFTWARE DEVELOPMENT RELATED TO FOREGOING

PARTICLE IMAGE VELOCIMETRY (PIV) VIA LASER DIAGNOSTIC METHODS







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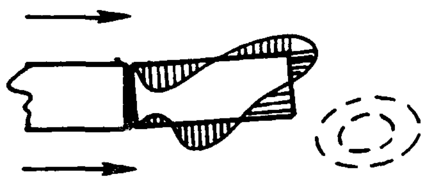
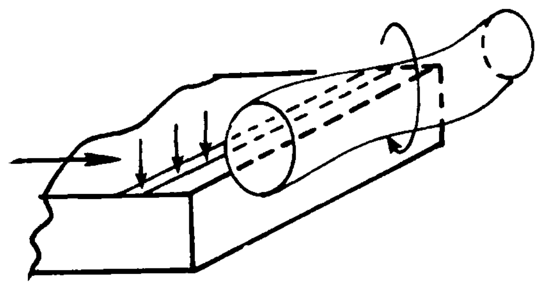
GENERIC EDGE/SURFACE INTERACTIONS

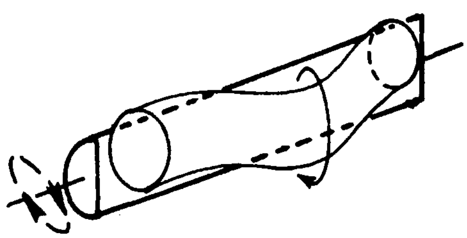
TRAILING-EDGE INTERACTIONS



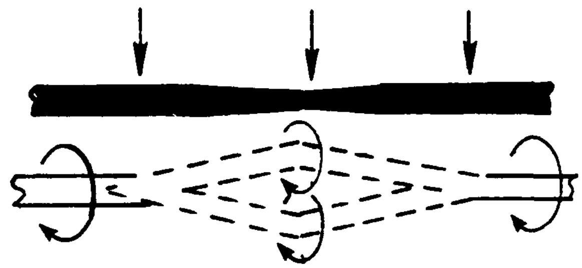
WAKE FROM TRAILING-EDGE UNDERGOING SINUSOIDAL PERTURBATIONS



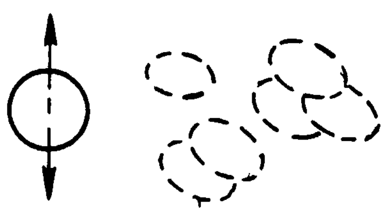
WAKE FROM STATIONARY TRAILING-EDGE WITH BOUNDARY-LAYER SUCTION



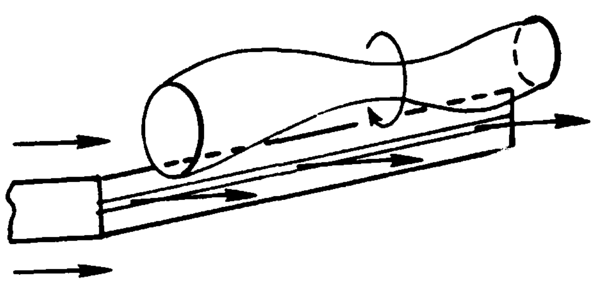
WAKE FROM D-CYLINDER UNDERGOING DUAL MODE EXCITATION



WAKE FROM MILDLY NONUNIFORM CYLINDER PERTURBED SINUSOIDALLY



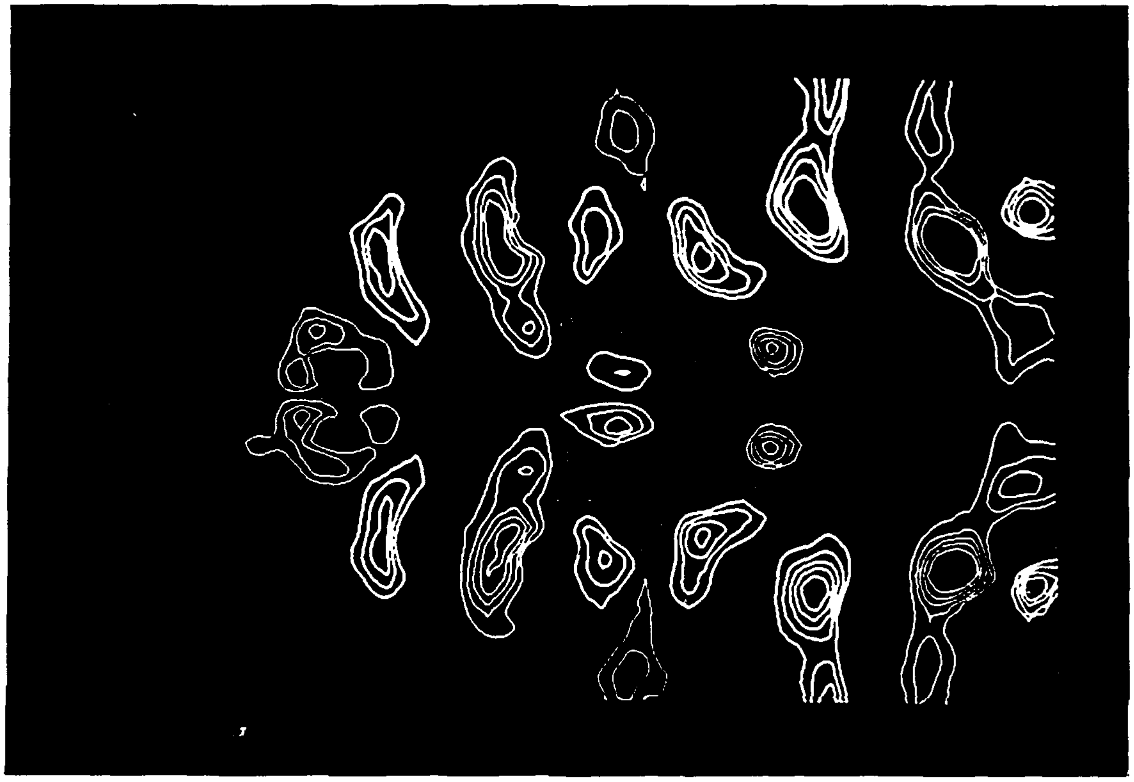
WAKE FROM CYLINDER UNDERGOING AMPLITUDE- AND FREQUENCY-MODULATED EXCITATION

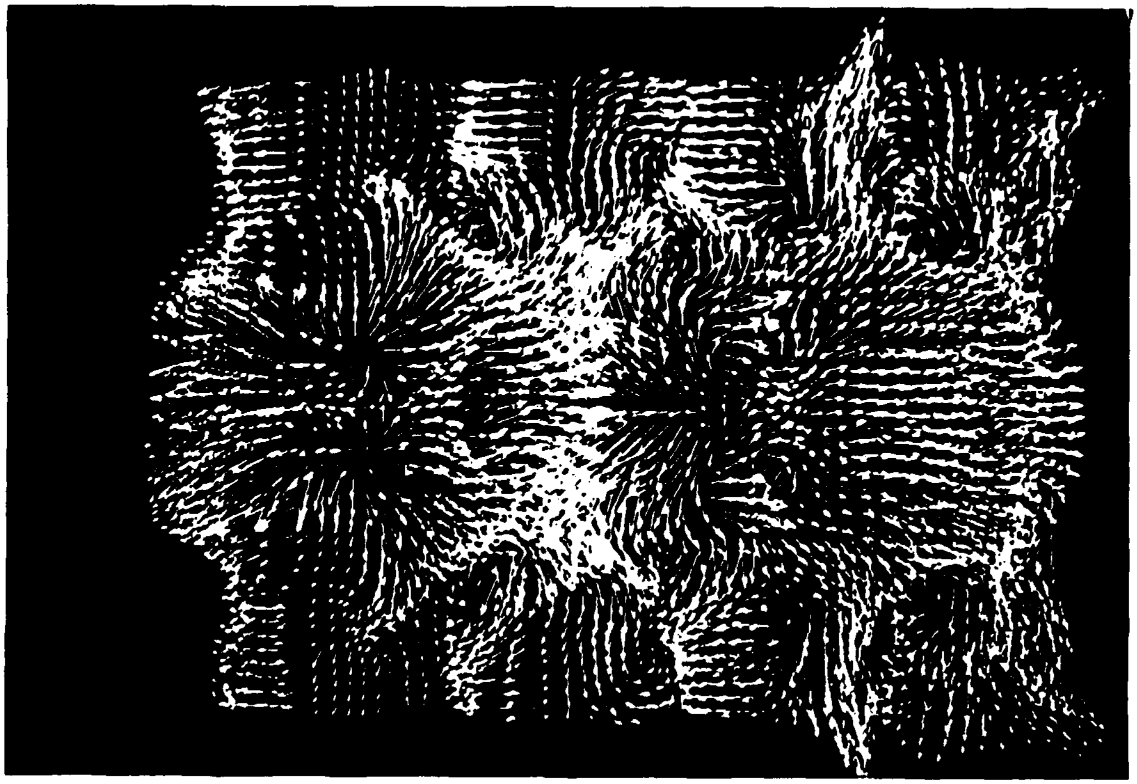


WAKE FROM STATIONARY TRAILING-EDGE WITH BASE BLOWING

GENERIC EDGE/SURFACE INTERACTIONS

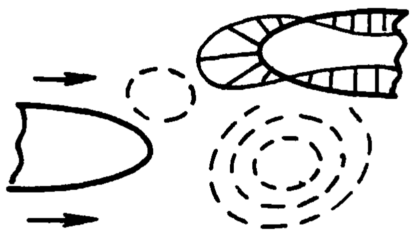
TRAILING-EDGE INTERACTIONS



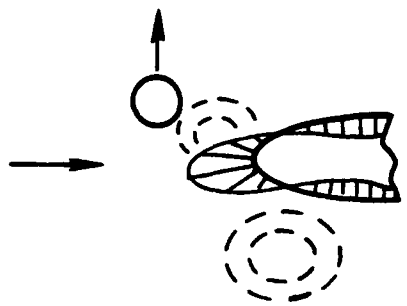


GENERIC EDGE/SURFACE INTERACTIONS

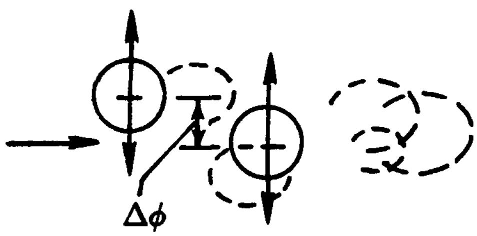
LEADING-EDGE INTERACTIONS



WAKE ASYMMETRICALLY INCIDENT
UPON LEADING-EDGE

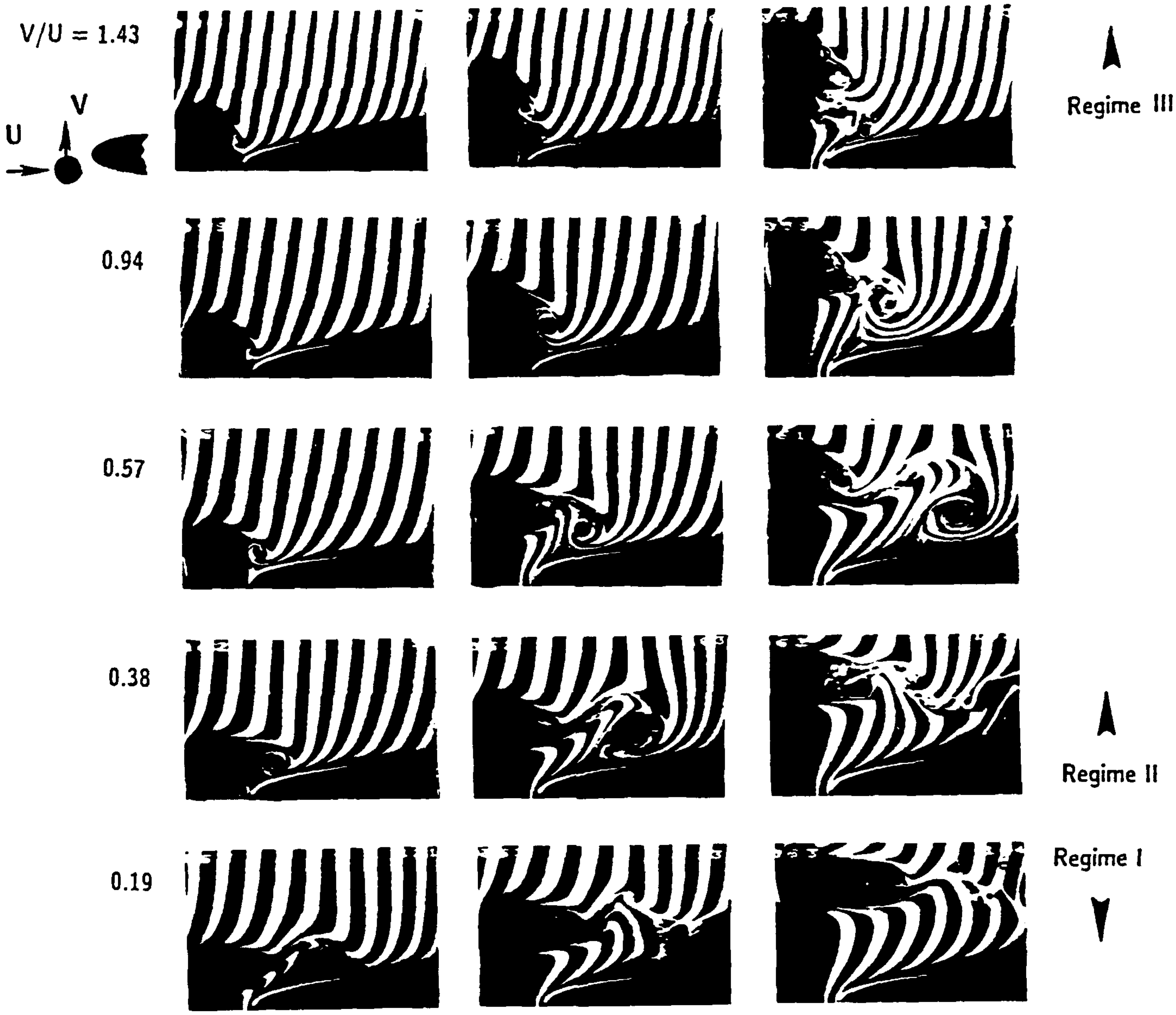


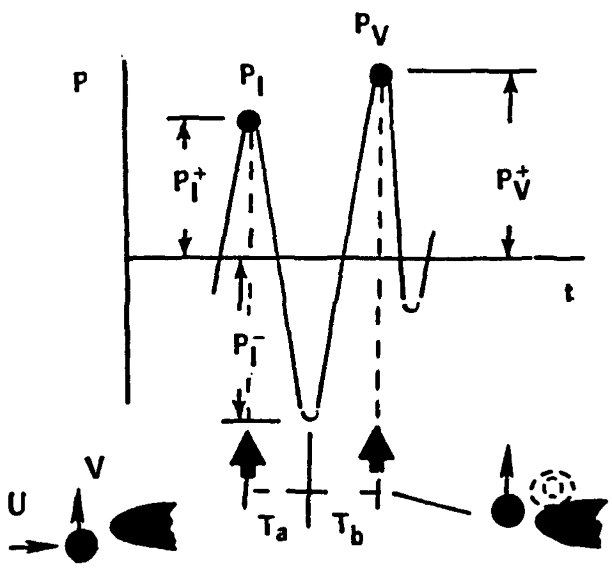
WAKE FROM GENERATOR
PAST LEADING-EDGE



WAKE-GAP INTERACTONS IN
SYSTEM OF OSCILLATING CYLINDERS

SIMULATED BLADE-BLADE INTERACTION: DEVELOPMENT OF VORTEX AND PRESSURE FIELDS





CYLINDER TO FREE-STREAM VELOCITY RATIO V/U DETERMINES RATE OF DEVELOPMENT OF LARGE-SCALE STRUCTURES IN GAP BETWEEN CYLINDER AND ELLIPTICAL LEADING-EDGE.

RELATIVE AMPLITUDES OF P_I (INVISCID) AND P_V (VORTICITY) PRESSURE PEAKS AND PHASE OF OCCURRENCE OF PEAKS (AT T_a AND T_b) ARE FUNCTIONS OF VELOCITY RATIO V/U AND DISTANCE ALONG LEADING-EDGE.

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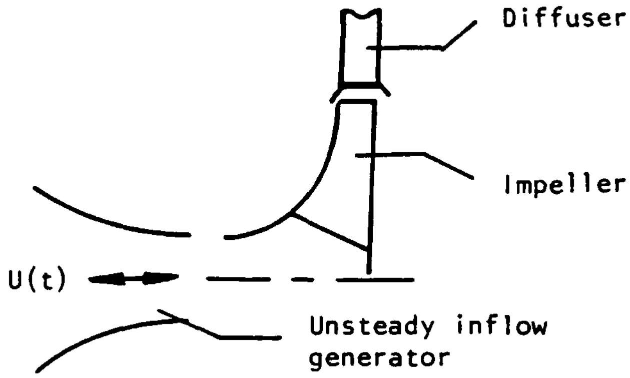
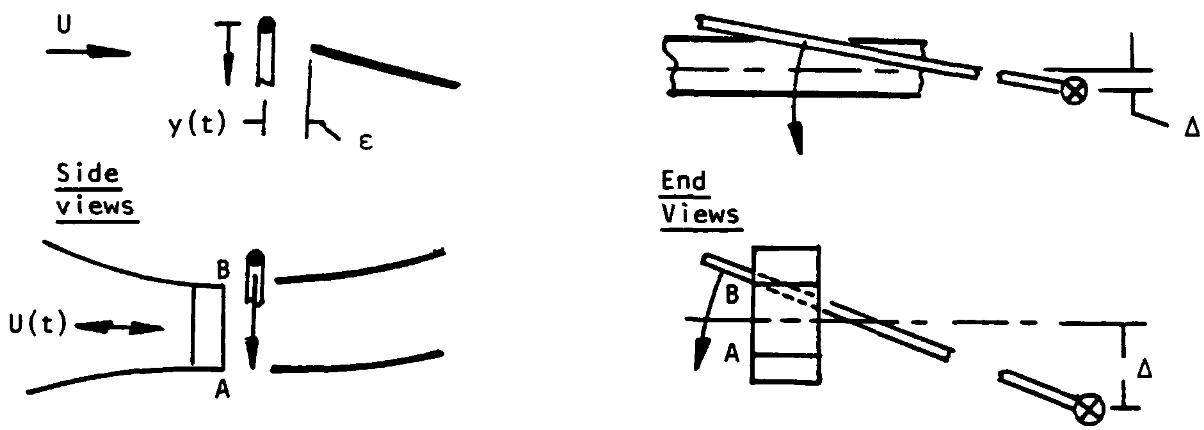
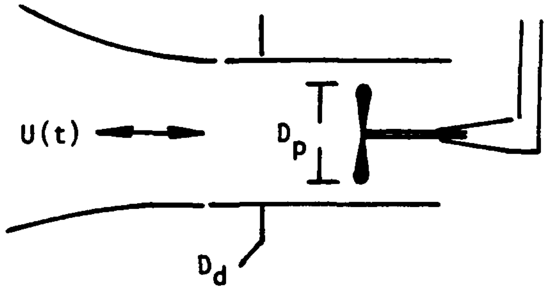
**CONTROLLED PUMP:
RADIAL FLOW IMPELLER-
DIFFUSER SYSTEM**



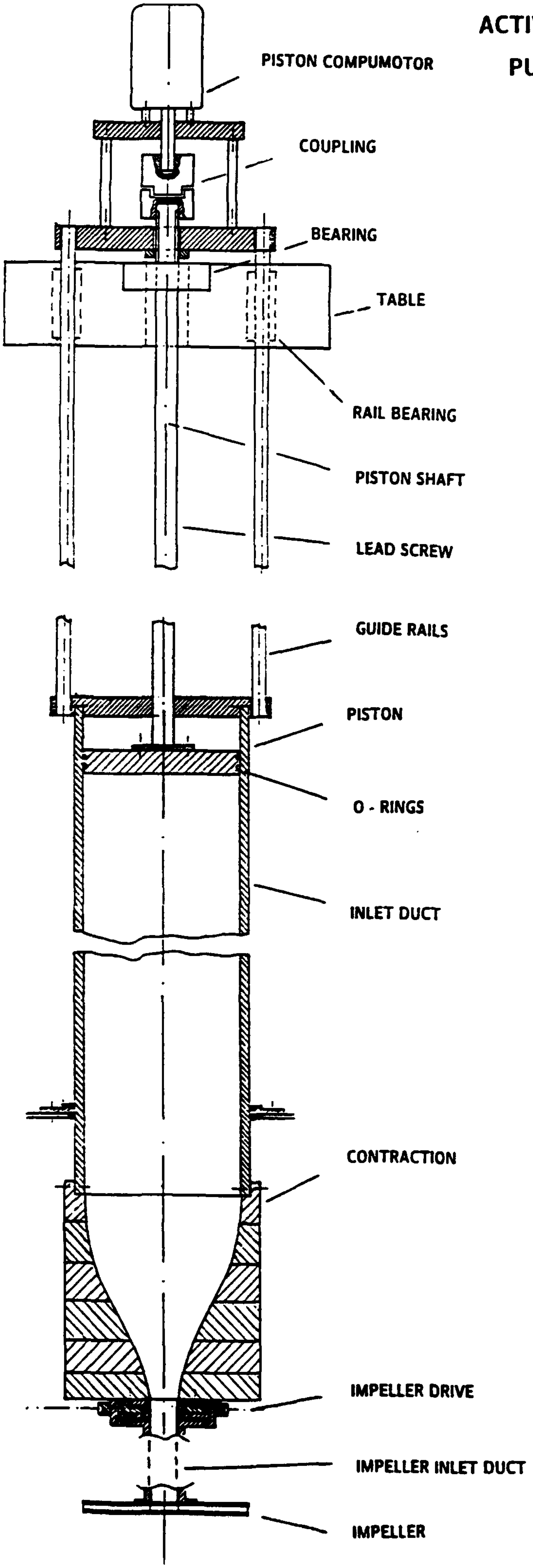
CONTROLLED WAKE-BLADE INTERACTION SYSTEM (PROJECTED)



**CONTROLLED AXIAL FLOW
PROPELLER SYSTEM (PROJECTED)**

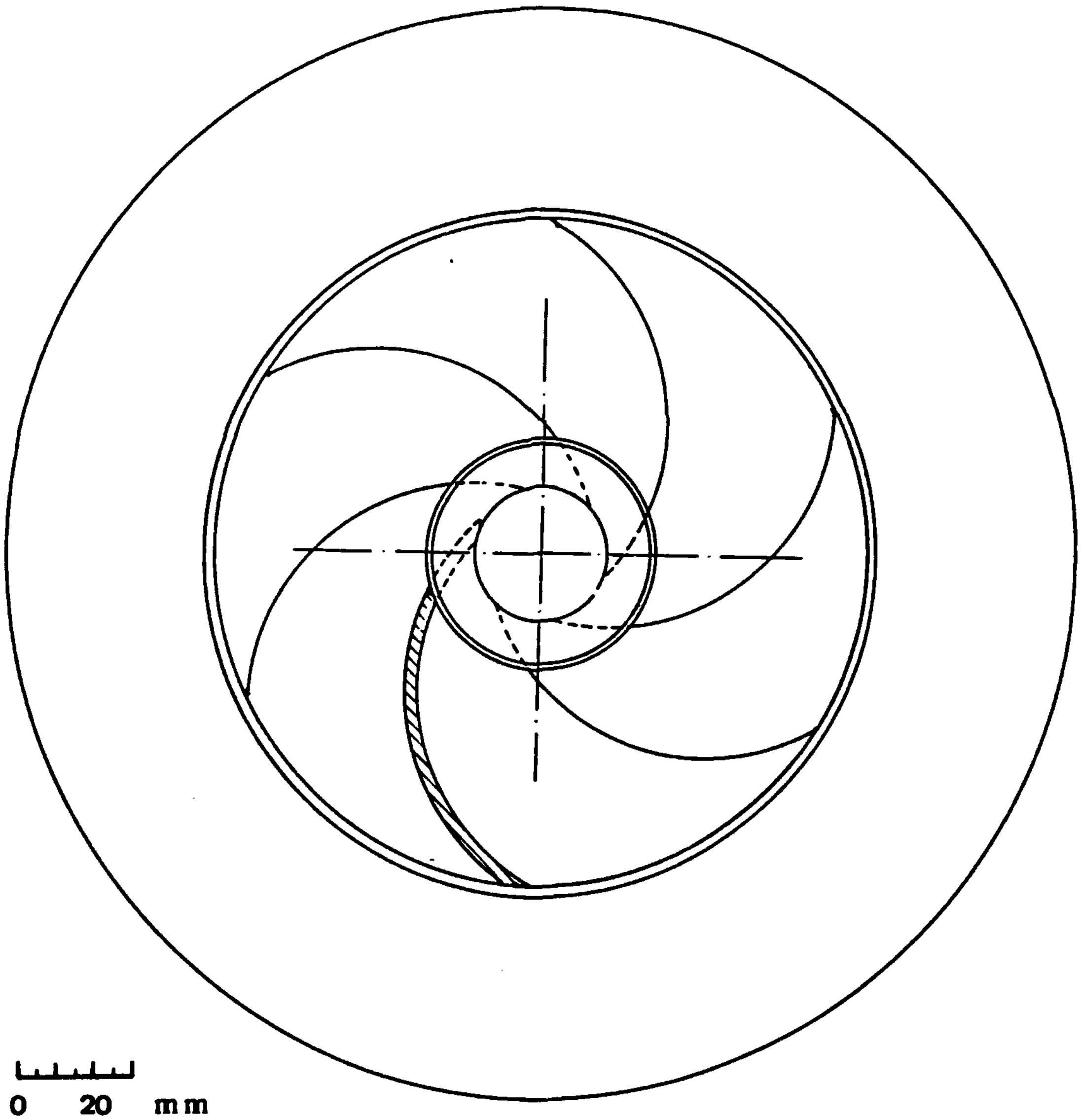


ACTIVELY-CONTROLLED PUMPING SYSTEM



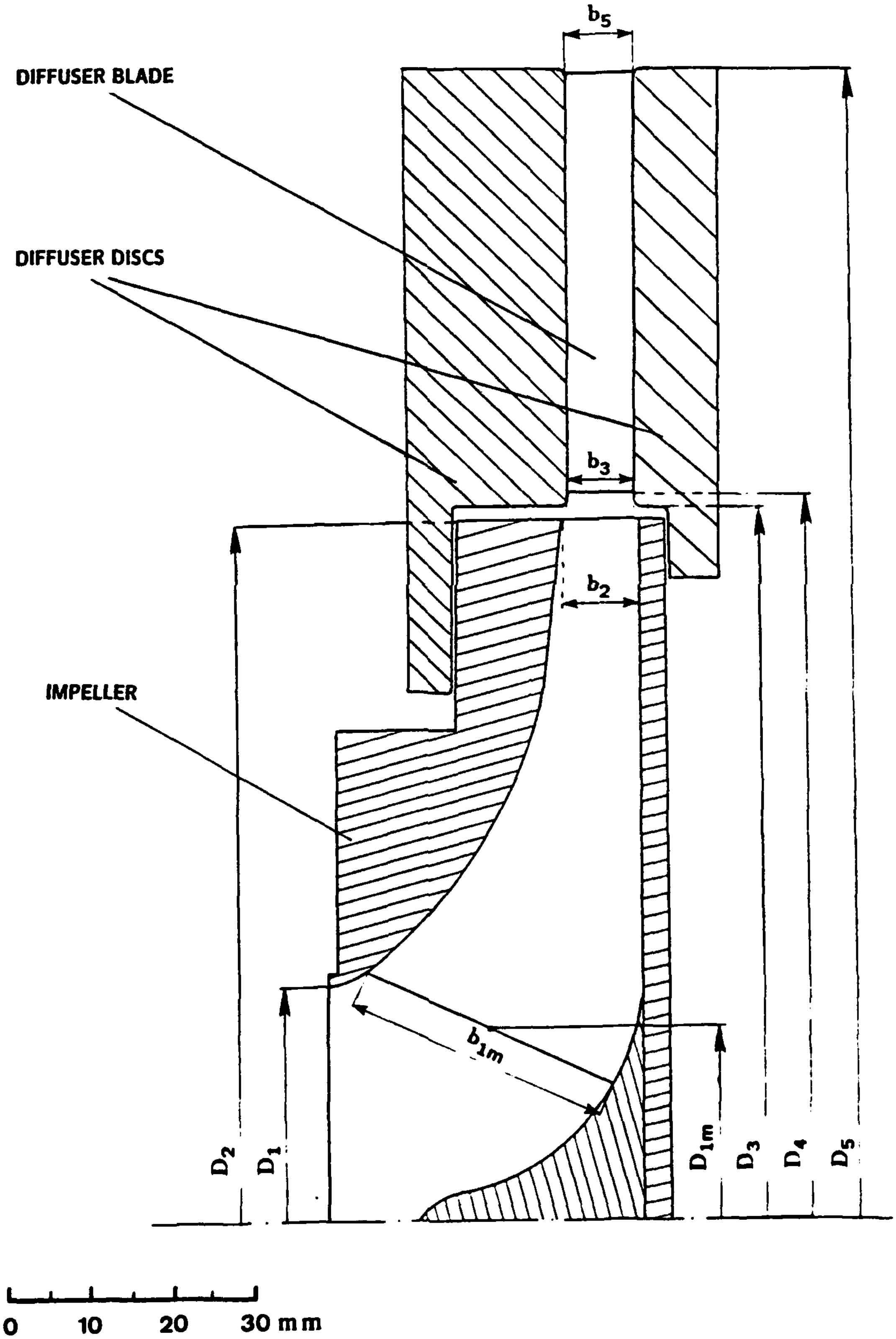
EXPERIMENTAL SYSTEMS

PLAN VIEW OF IMPELLER-VANELESS DIFFUSER SYSTEM



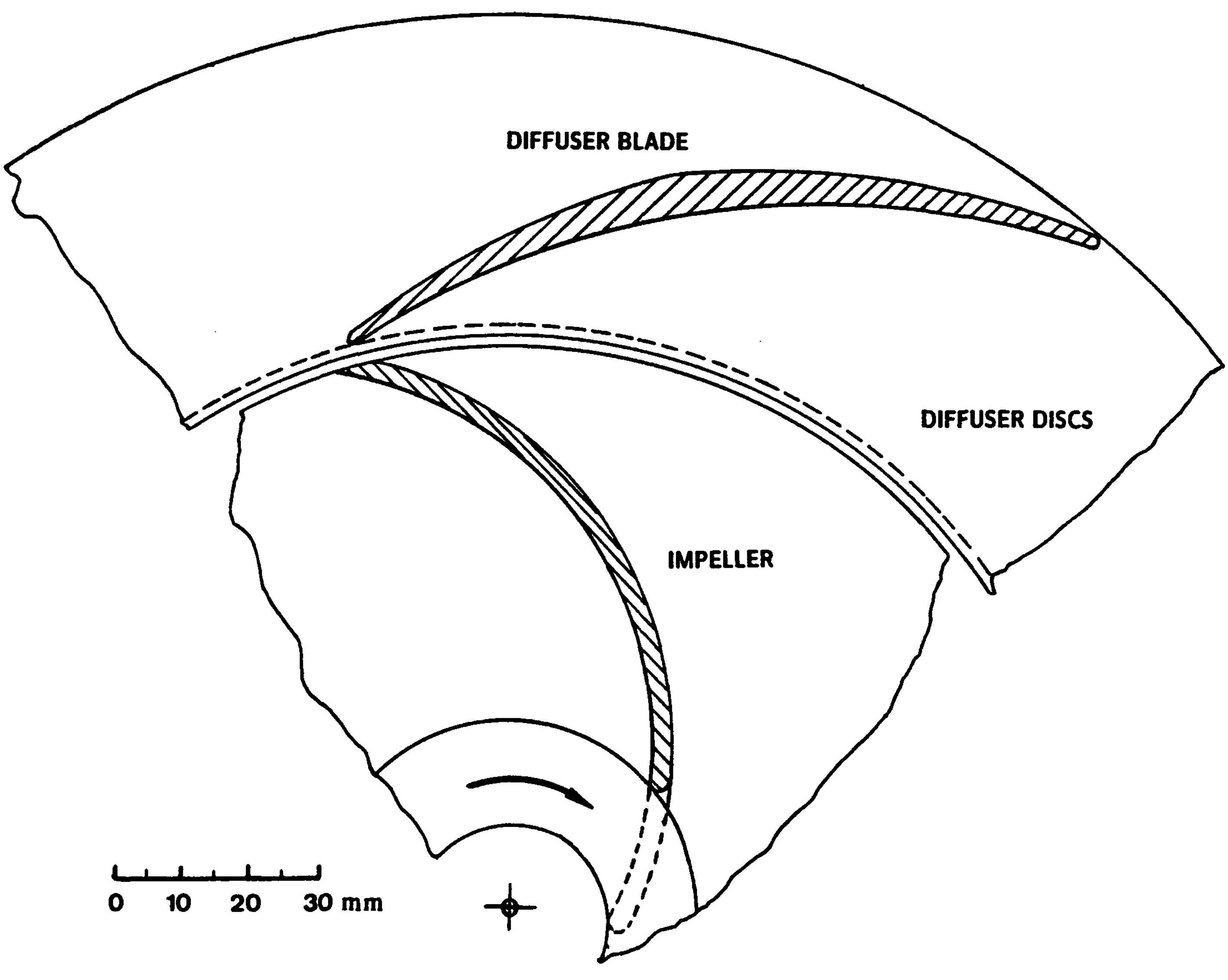
EXPERIMENTAL SYSTEMS

CROSS-SECTIONAL VIEW OF
IMPELLER-DIFFUSER SYSTEM

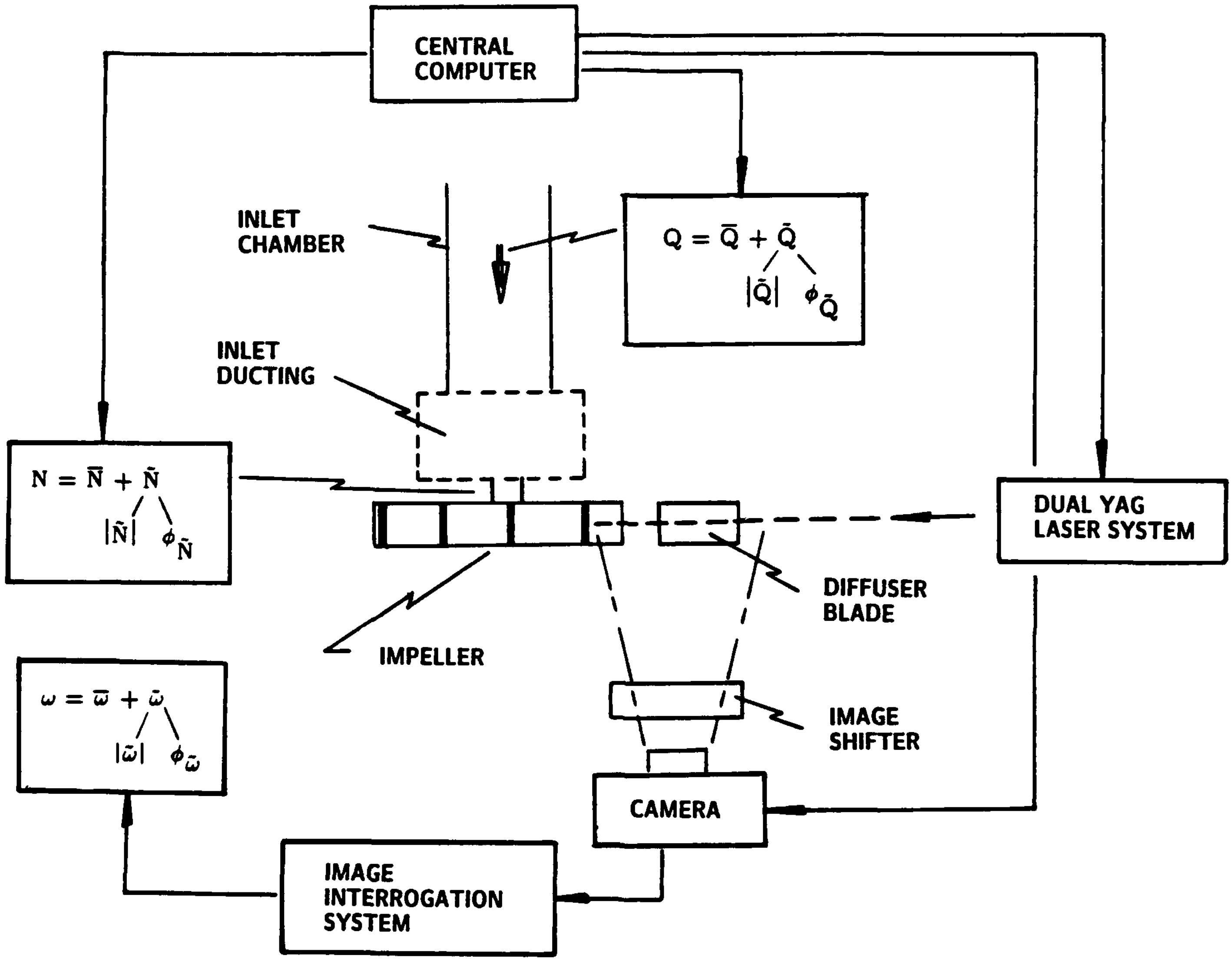


EXPERIMENTAL SYSTEMS

PLAN VIEW OF
IMPELLER-DIFFUSER
BLADE SYSTEM



EXPERIMENTAL SYSTEMS: INTEGRATED ACTIVE CONTROL - FLOW VISUALIZATION SYSTEM



- INLET FLOW Q AND IMPELLER ROTATION N HAVE ARBITRARY FUNCTIONAL FORMS AND PHASE SHIFTS.

- CENTRAL COMPUTER CONTROLS FLOW Q, ROTATION, AND MULTIPLE FIRING OF YAG LASER SYSTEM AND CAMERA SYSTEM.

- CAMERA-IMAGE INTERROGATION SYSTEM GIVES INSTANTANEOUS VELOCITY AND VORTICITY FIELDS.

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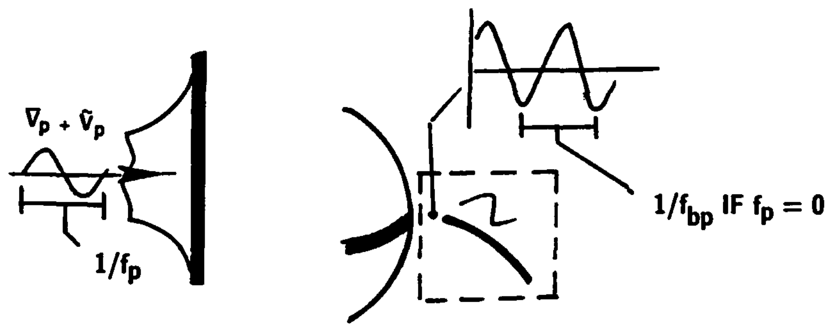
OVERALL RESPONSE TO CONTROLLED EXCITATION: GENERATION OF MODULATED SPECTRAL COMPONENTS AND FLOW STRUCTURE—HYPOTHESIZED MECHANISMS



(a) IN ABSENCE OF INFLOW PULSATIONS AT f_p, FLOW STRUCTURE TENDS TO REPEAT WITH PERIOD $1/f_{bp}$.

(b) IN PRESENCE OF INFLOW PULSATIONS AT f_p, FLOW STRUCTURE TENDS TO REPEAT AT DIFFERENCE FREQUENCY $f_p - f_{bp}$ AND ITS NONLINEAR HARMONICS.

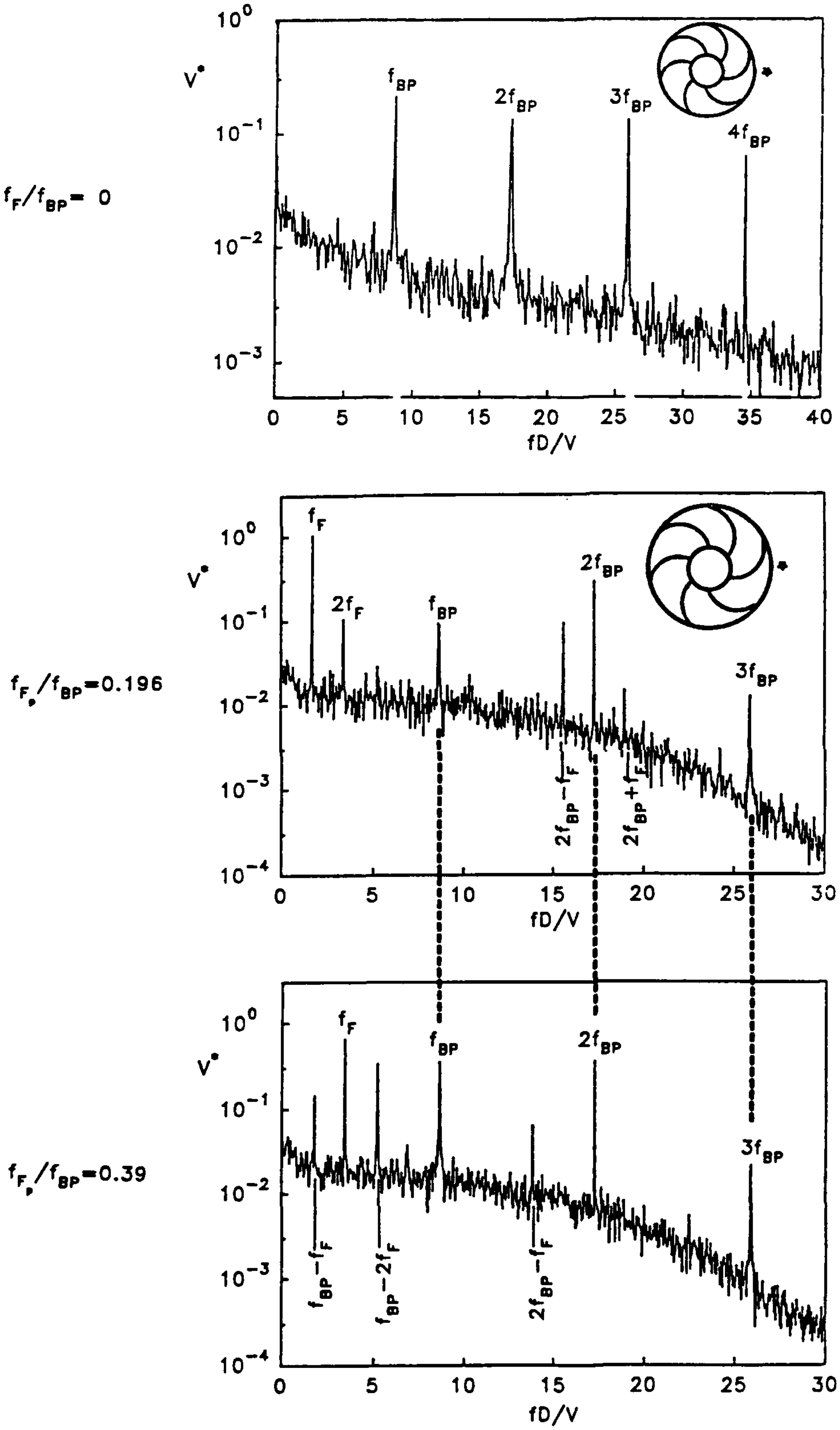
(c) REINFORCEMENT OF THESE COMPONENTS AND GENERATION OF ADDITIONAL DISCRETE COMPONENTS CAN ARISE FROM NONLINEAR INTERACTION BETWEEN f_p AND f_{bp} IN BOUNDARY LAYER OR SEPARATING SHEAR LAYER TO GIVE $nf_p \pm mf_{bp}$.

(d) IF INFLOW FORCING HAS AMPLITUDE- OR FREQUENCY-MODULATED FORM, THEN LARGE NUMBER OF SUM AND DIFFERENCE COMPONENTS IS EXPECTED DUE TO MULTIPLE SIDEBAND INTERACTIONS.

(e) FOREGOING PROCESSES CAN INFLUENCE RATE AT WHICH SPECTRAL BROADENING OCCURS.

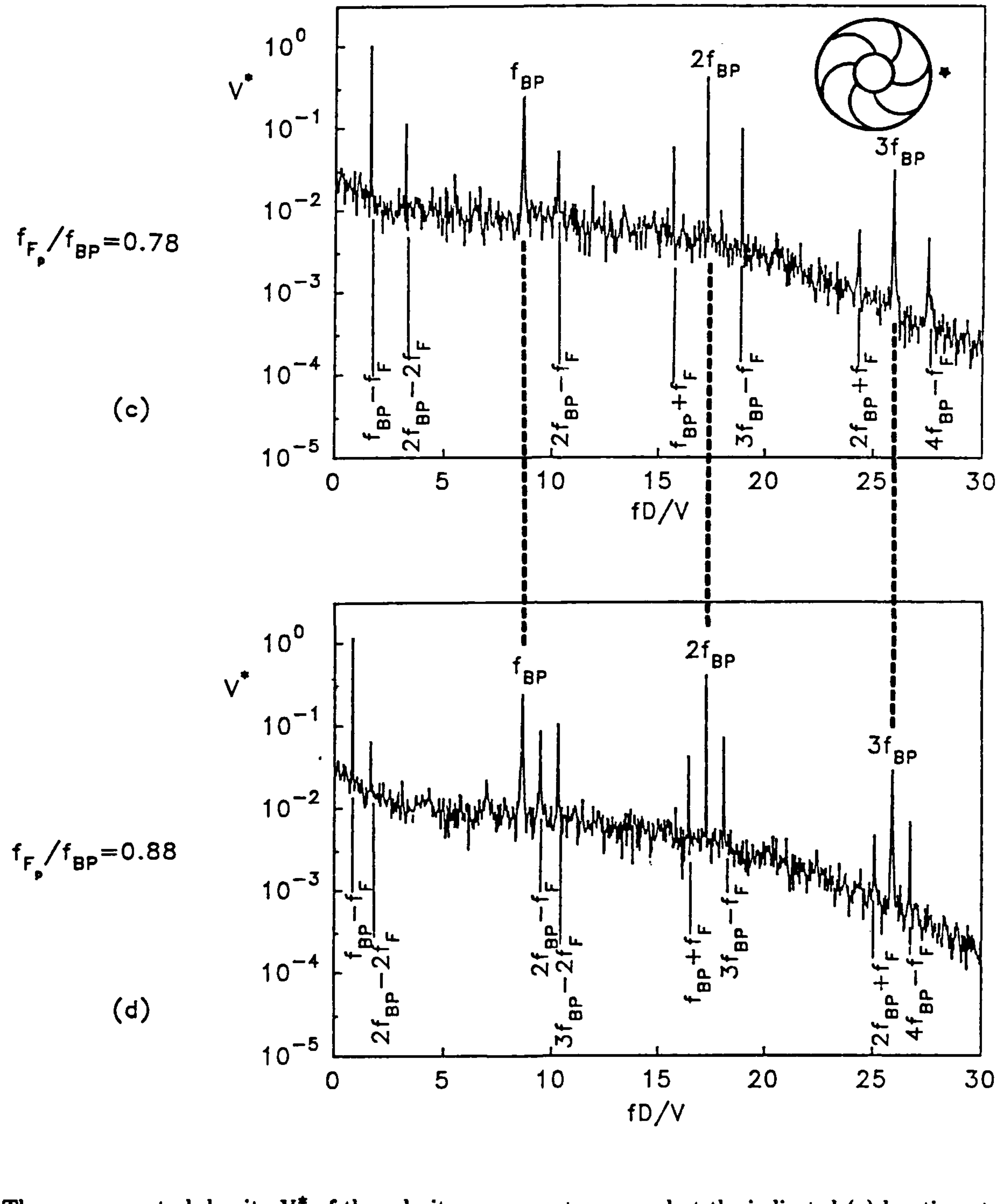
(f) SPECTRAL BROADENING SHOULD BE ENHANCED BY EXISTENCE OF ADVERSE PRESSURE GRADIENT (VANELESS DIFFUSER) OR SEPARATION ZONES (DIFFUSER OR CUTOFF BLADES).

OVERALL RESPONSE TO CONTROLLED EXCITATION: GENERATION OF NONLINEAR INTERACTION COMPONENTS



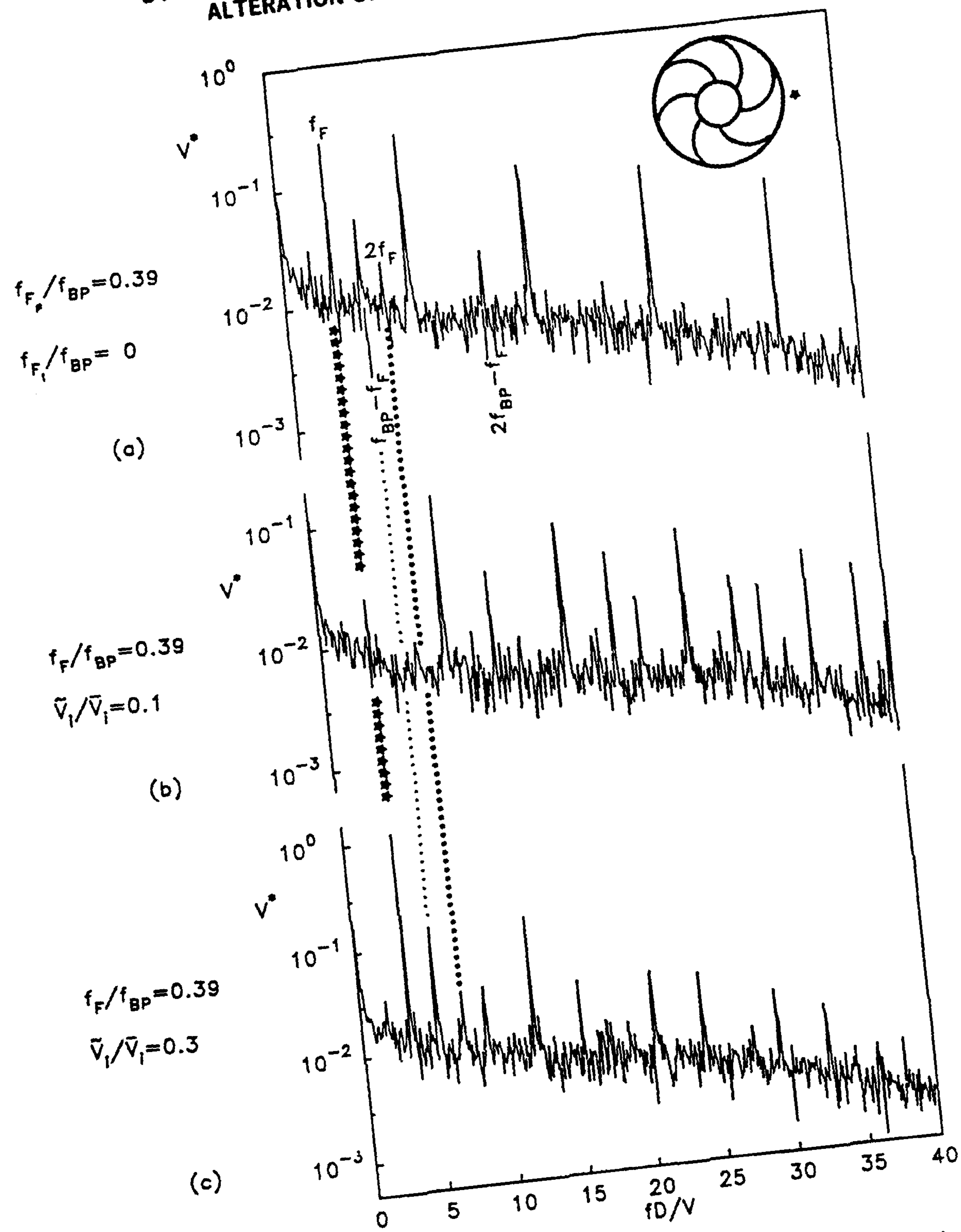
The power spectral density of the velocity fluctuation V^* is measured at the indicated (*) location at the exit of the impeller. At a relatively low value of the inflow perturbation frequency f_F, relative to the blade passing frequency, f_{BP}, i.e. $f_F/f_{BP} = 0.196$, only the first harmonic $2f_F$, as well as nonlinear interaction components with $2f_{BP}$ are present. Increasing the dimensionless inflow perturbation frequency to $f_F/f_{BP} = 0.39$ produces pronounced sum and difference components between f_F and f_{BP}.

OVERALL RESPONSE TO CONTROLLED EXCITATION: ATTENUATION OF FORCING COMPONENT AND GENERATION OF NONLINEAR INTERACTIONS



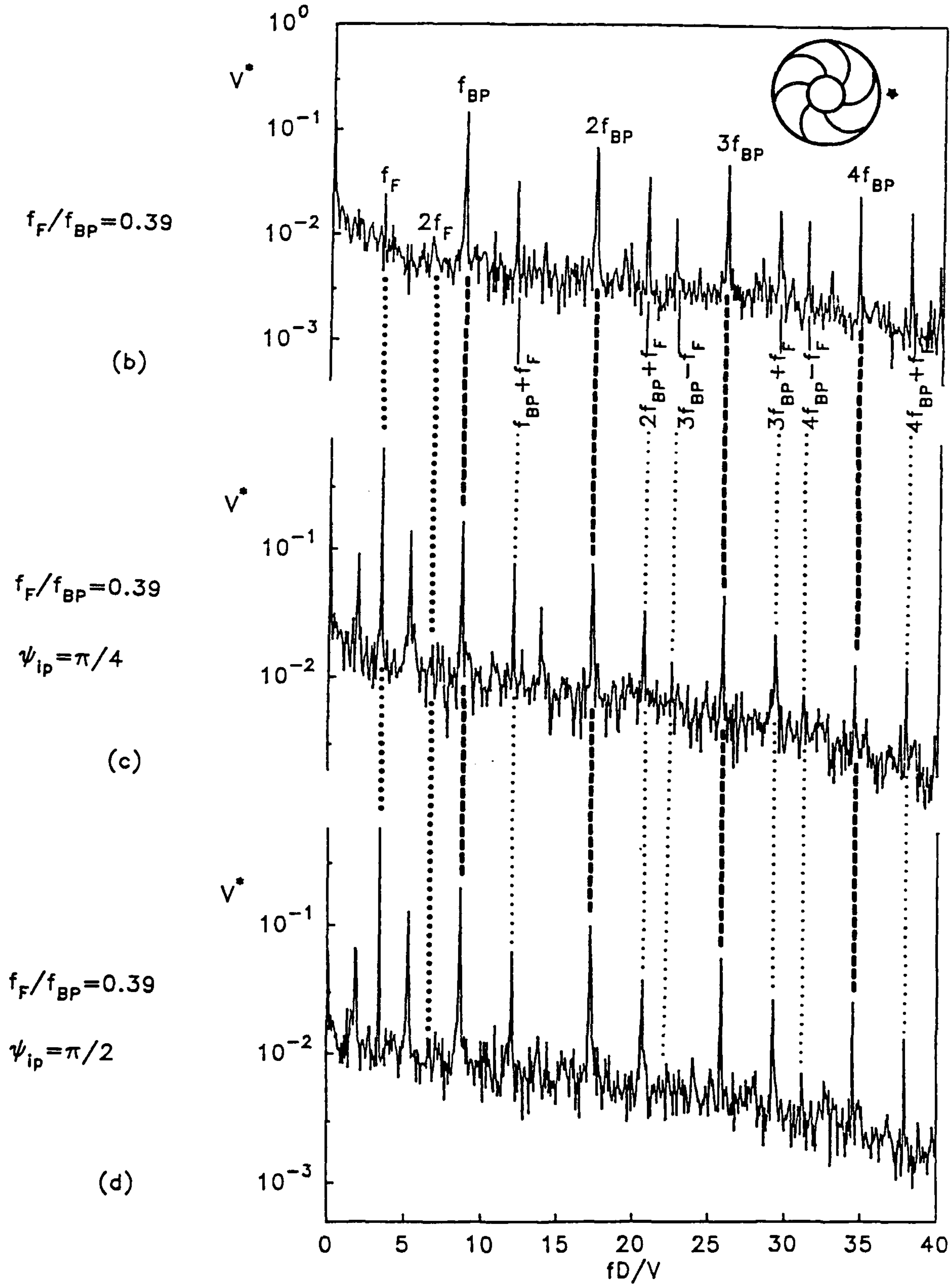
The power spectral density V^* of the velocity component measured at the indicated (*) location at the impeller discharge exhibits a large number of nonlinear interaction components between the inflow forcing frequency f_F and the blade passing frequency f_{BP}. However, at these relatively high values of dimensionless forcing frequency f_F/f_{BP} = 0.78 and 0.88, the spectral peak at the inflow forcing frequency f_F is completely attenuated.

OVERALL RESPONSE TO CONTROLLED EXCITATION: ALTERATION OF FORCING COMPONENT



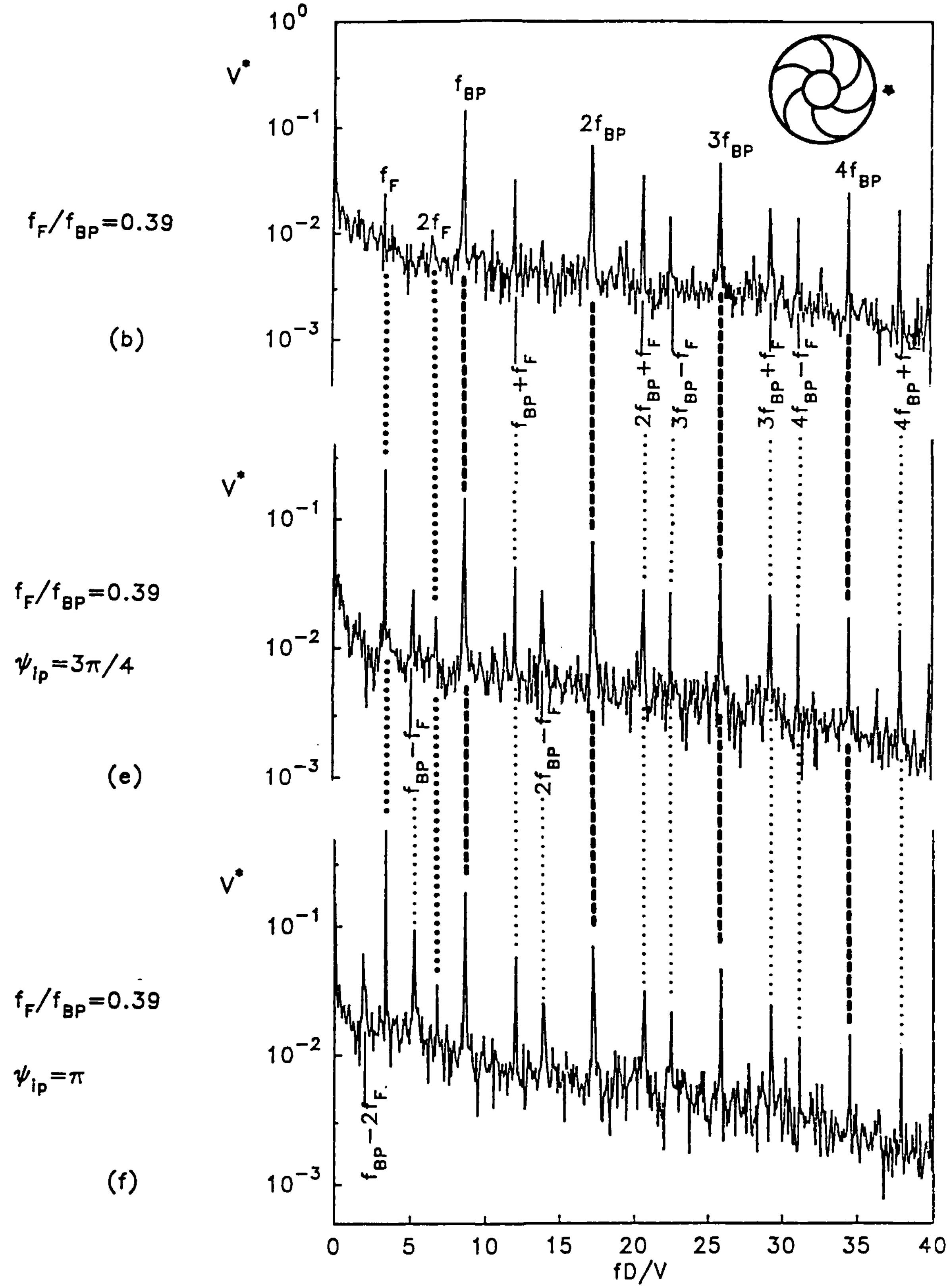
The power spectral density of the velocity fluctuation V^* is measured at the discharge of the impeller. The amplitude of the component at the inflow forcing frequency f_F, as well as the amplitude of higher order spectral components, is strongly dependent upon the amplitude of the tangential velocity fluctuation $\tilde{V}_i$ of the impeller relative to its mean tangential velocity $\bar{V}_i$. In the top plot, only the inflow is perturbed at a dimensionless frequency $f_F/f_{BP} = 0.39$. In the middle plot, the inflow is perturbed with the same condition, but accompanied by in-phase perturbations of the tangential velocity of the impeller at an amplitude of $\tilde{V}_i/\bar{V}_i = 0.1$; the amplitude of the component at forcing frequency f_F is nearly attenuated. In the bottom plot, the same excitation conditions hold as for the middle plot, except the dimensionless amplitude is increased to a value of $\tilde{V}_i/\bar{V}_i = 0.3$; the amplitude of the component f_F is actually amplified relative to that in the top plot. Consideration of a range of excitation conditions shows that the amplitude of the spectral component f_F is highly sensitive to the amplitude of the impeller perturbation $\tilde{V}_i/\bar{V}_i$; extremes of either complete attenuation or substantial amplification are attainable.

OVERALL RESPONSE TO CONTROLLED EXCITATION: ALTERATION OF FORCING COMPONENT



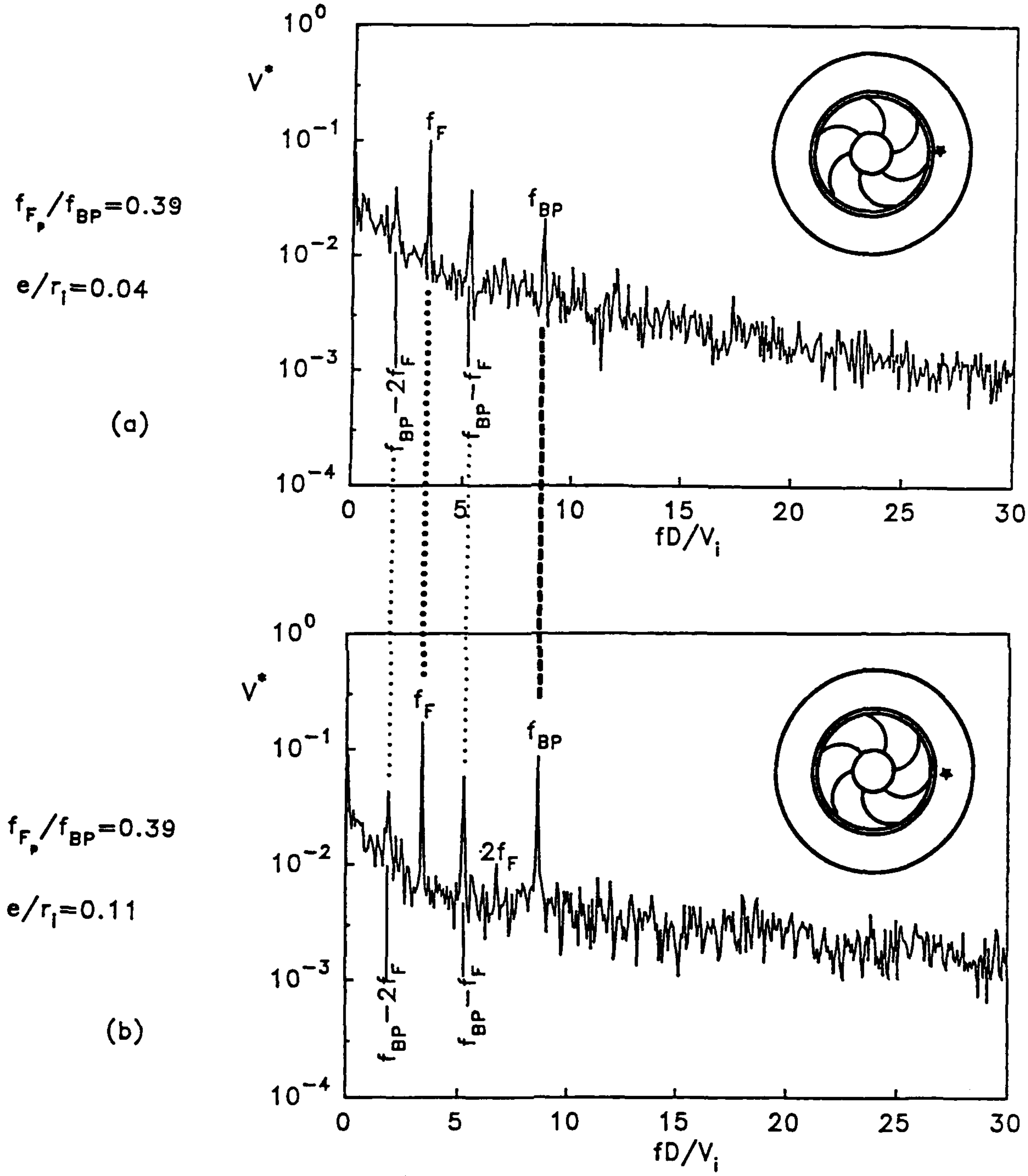
The power spectral density V^* of the velocity fluctuation is measured at the indicated (*) location at the impeller discharge. Excitation of the inflow only at a dimensionless frequency $f_F/f_{BP} = 0.39$, where f_F is the forcing frequency and f_{BP} is the blade passing frequency, is represented by the top plot. In the middle and bottom plots, there is simultaneous excitation of the inflow velocity and the impeller tangential velocity, with the phase angle ψ_{ip} between them.

OVERALL RESPONSE TO CONTROLLED EXCITATION: ALTERATION OF FORCING COMPONENT



The power spectral density V* of the velocity fluctuation is measured at the indicated (*) location at the impeller discharge. Excitation of the inflow only at a dimensionless frequency $f_F/f_{BP} = 0.39$ is shown in the top plot. In the middle and bottom plots, there is simultaneous excitation of the inflow velocity and the impeller tangential velocity, with the phase angle ψ_{ip} between them. The amplitudes of the spectral peaks in the lower frequency range are strongly influenced by the value of ψ_{ip}.

OVERALL RESPONSE TO CONTROLLED EXCITATION: DECAY OF DISCRETE SPECTRAL COMPONENTS IN VANELESS DIFFUSER



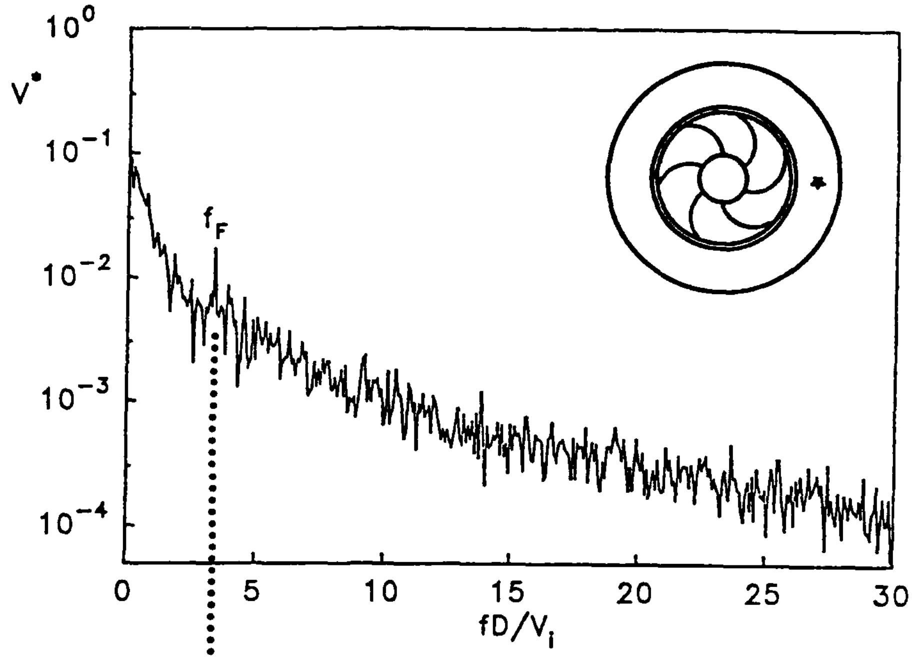
The power spectral density V* of the velocity component is measured at the indicated (*) location within the vaneless diffuser. Excitation of the inflow is at a dimensionless frequency f_F/f_{BP} = 0.39. As the distance e, relative to the radius r_i of the impeller, increases, the amplitudes of the discrete spectral components are altered. At large distances, the discrete spectral components are immersed in the broadband level.

OVERALL RESPONSE TO CONTROLLED EXCITATION: DECAY OF DISCRETE SPECTRAL COMPONENTS IN VANELESS DIFFUSER

$f_{F_p}/f_{BP}=0.39$

$e/r_i=0.19$

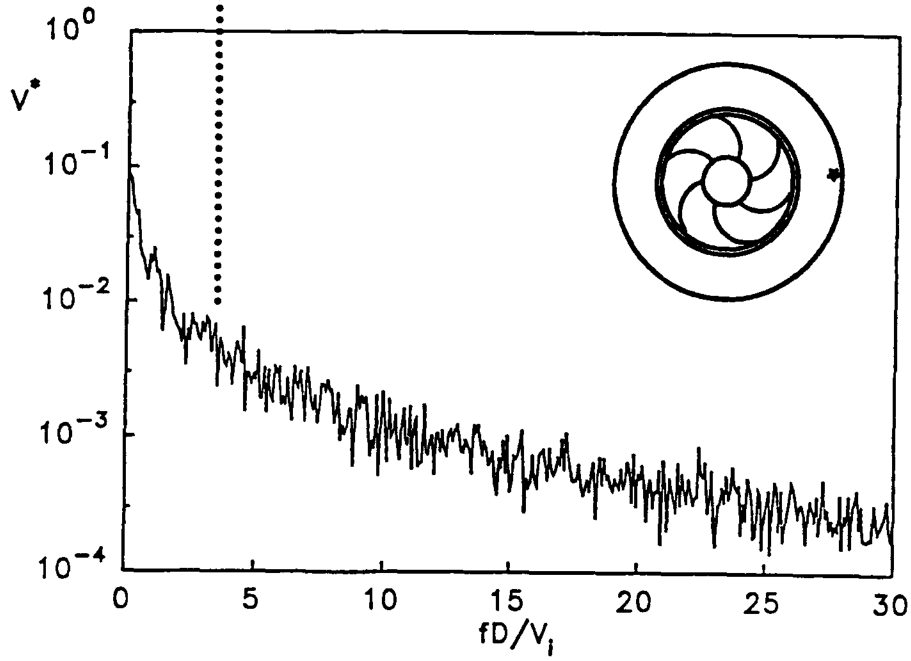
(c)



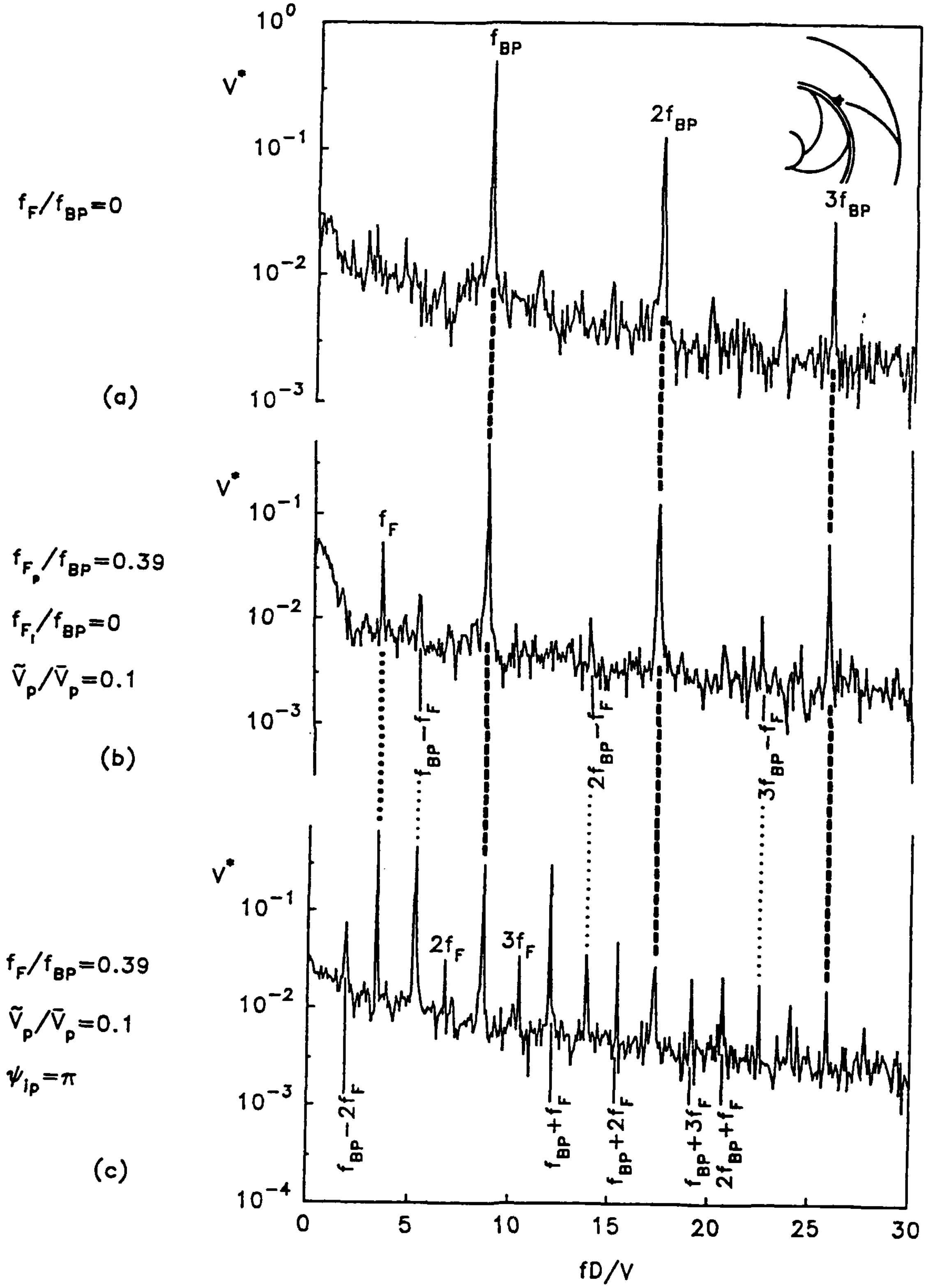
$f_{F_p}/f_{BP}=0.39$

$e/r_i=0.44$

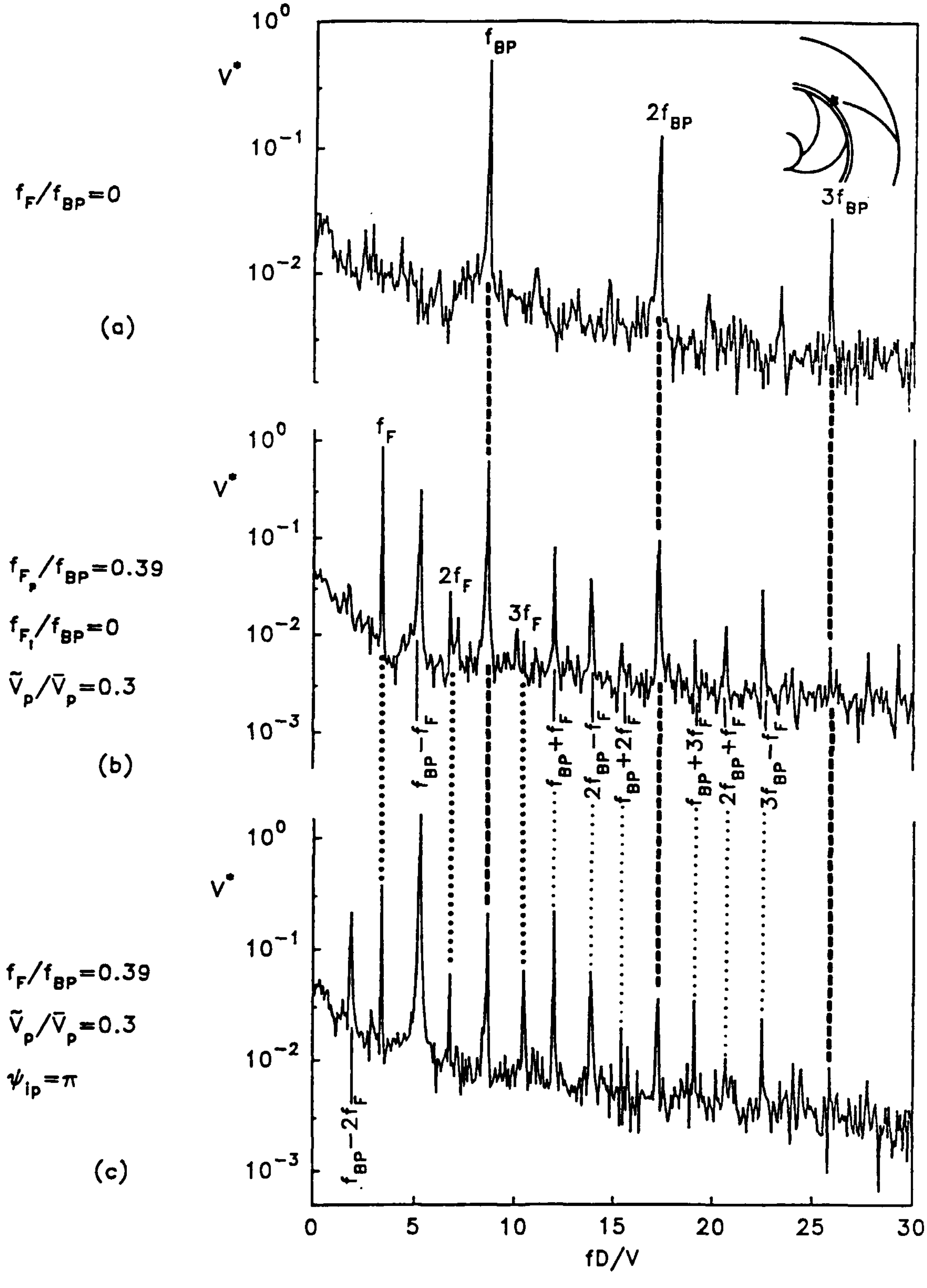
(d)



EFFECTS OF CONTROLLED EXCITATION IN PRESENCE OF DIFFUSER BLADE: EFFECTS OF INFLOW AND IMPELLER PERTURBATIONS

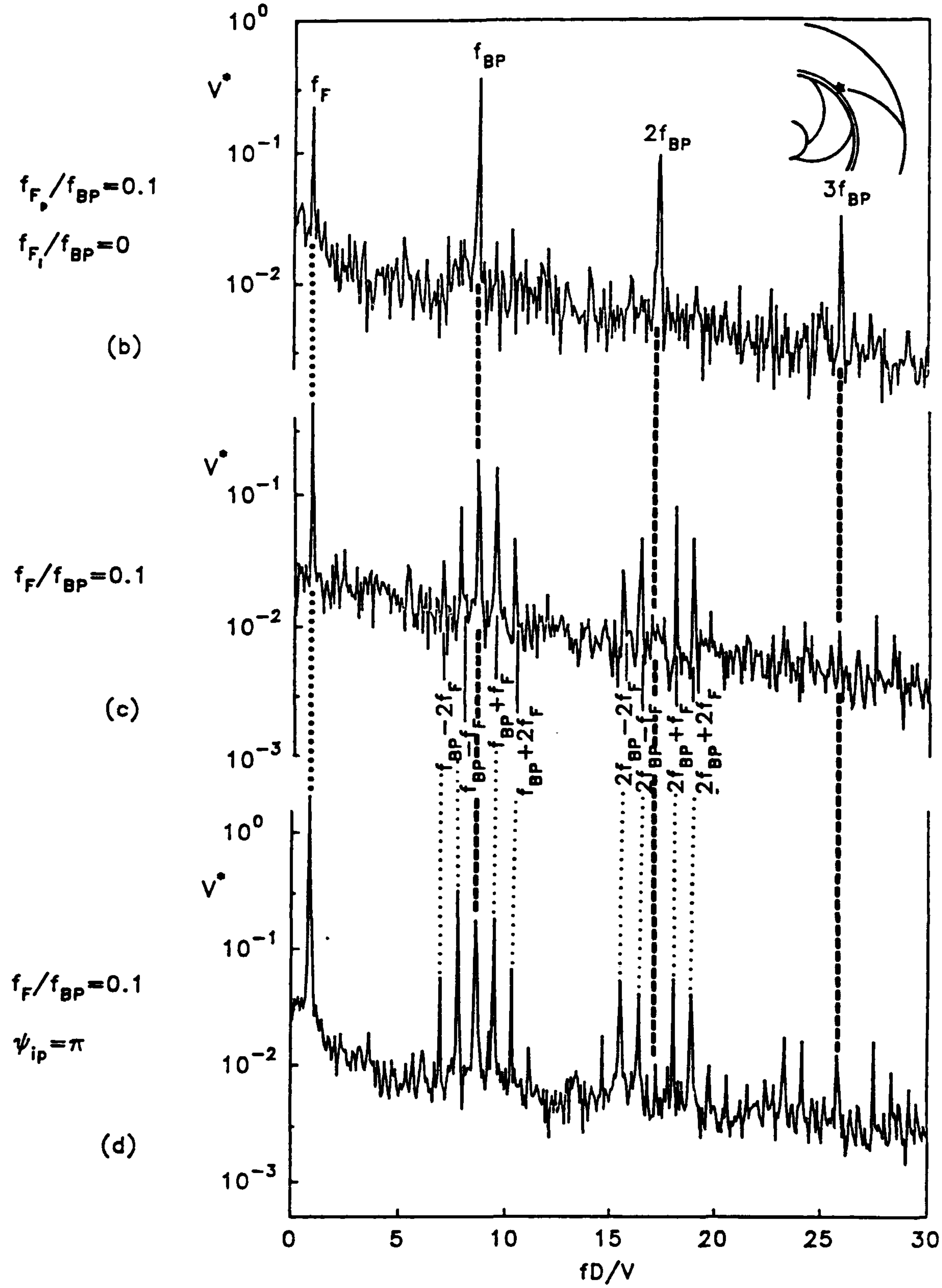


The amplitude of the power spectral density V^* of the velocity fluctuation is measured at indicated (∗) location between discharge of impeller and leading-edge of stationary diffuser blade. In the top plot, no external forcing is imposed. In the middle plot, there is forcing only of the inlet flow at an excitation frequency f_{F_p} relative to the blade passing frequency f_{BP}, i.e. $f_{F_p}/f_{BP} = 0.39$ and at an amplitude of the inflow velocity $\tilde{V}_p$ relative to the mean inflow velocity of $\bar{V}_p$, $\tilde{V}_p/\bar{V}_p = 0.1$. Finally, in the bottom plot, the same excitation conditions were applied for the inflow, but in presence of a perturbation of the tangential velocity of the impeller at a phase angle $\psi_{ip} = \pi$ relative to the inflow perturbation. Very substantial manipulation of the discrete spectral components is attainable, especially in the presence of simultaneous inflow and impeller perturbations.



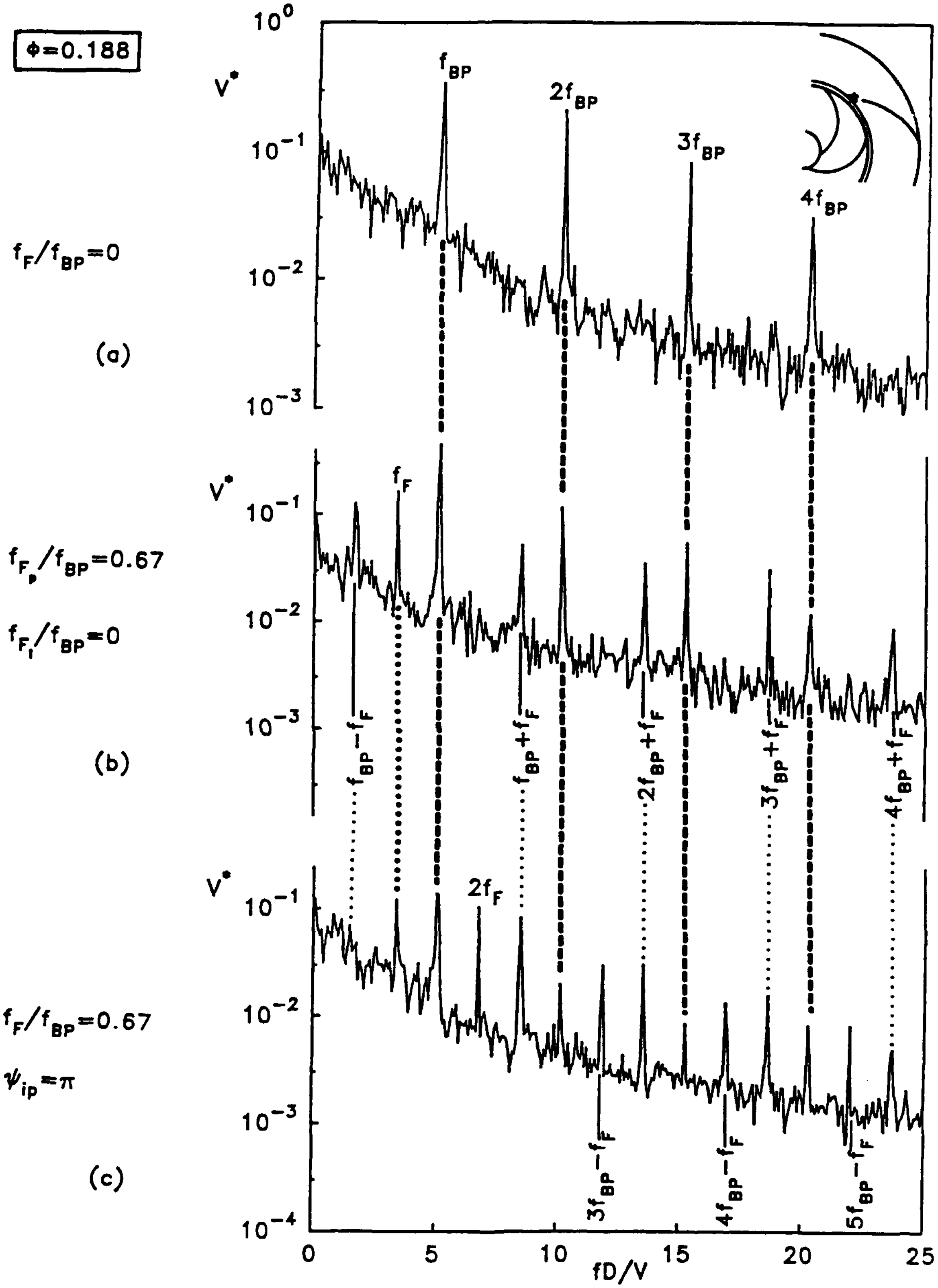
The amplitude of the power spectral density V^* of velocity fluctuation is measured at the indicated (*) location between the discharge of the impeller and the leading-edge of the stationary diffuser blade. In the top plot, no external forcing is imposed. In the middle plot, there is forcing only of the inlet flow at an excitation frequency f_{F_p} relative to the blade passing frequency f_{BP}, i.e. $f_{F_p}/f_{BP} = 0.39$ and at an amplitude of the inflow velocity $\tilde{V}_p$ relative to the mean inflow velocity of $\bar{V}_p$, $\tilde{V}_p/\bar{V}_p = 0.3$. Finally, in the bottom plot, the same excitation conditions were applied for the inflow, but in presence of a perturbation of the tangential velocity of the impeller at a phase angle $\psi_{ip} = \pi$ relative to the inflow perturbation. Very substantial manipulation of the discrete spectral components is attainable, especially in the presence of simultaneous inflow and impeller perturbations.

EFFECTS OF CONTROLLED EXCITATION IN PRESENCE OF DIFFUSER BLADE: EFFECTS OF INFLOW AND IMPELLER PERTURBATIONS



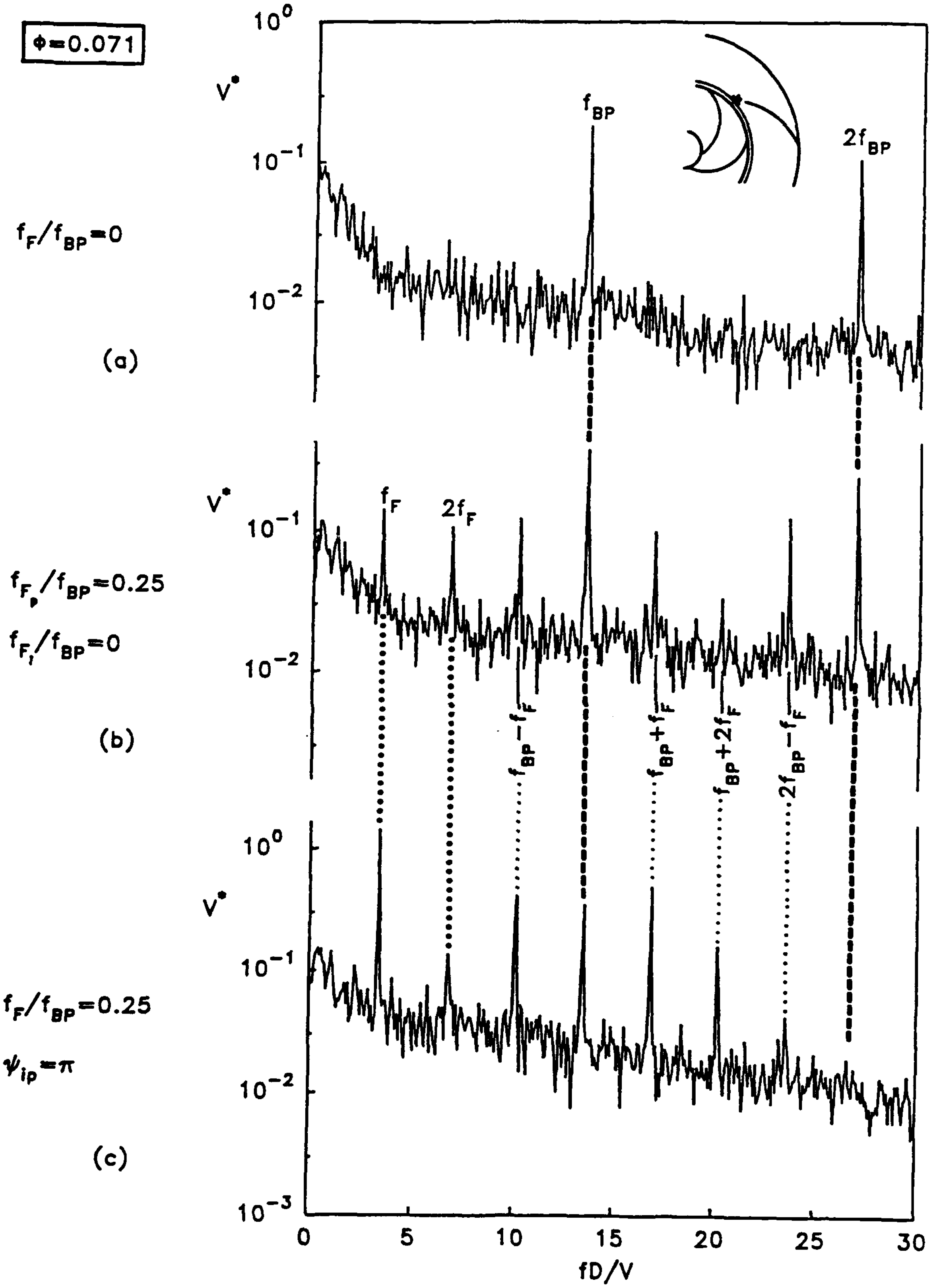
The power spectral density V^* of the velocity fluctuation is measured in the gap between the discharge of the impeller and the leading-edge of the diffuser blade. In the top plot, only the inflow is perturbed at a relatively low forcing frequency f_{F_p} relative to the blade passing frequency f_{BP}, i.e. f_{F_p}/f_{BP} = 0.1. In the middle plot, both the inflow and impeller are perturbed with zero phase angle between them, and in the bottom plot both the inflow and impeller are perturbed with a phase shift $\psi_{ip} = \pi$ between them. These results show that at this relatively low value of excitation frequency f_F/f_{BP} = 0.1, it is necessary to perturb both the inflow and impeller in order to generate a large number of nonlinear interaction components.

EFFECTS OF CONTROLLED EXCITATION IN PRESENCE OF DIFFUSER BLADE: EFFECTS OF INFLOW AND IMPELLER PERTURBATIONS



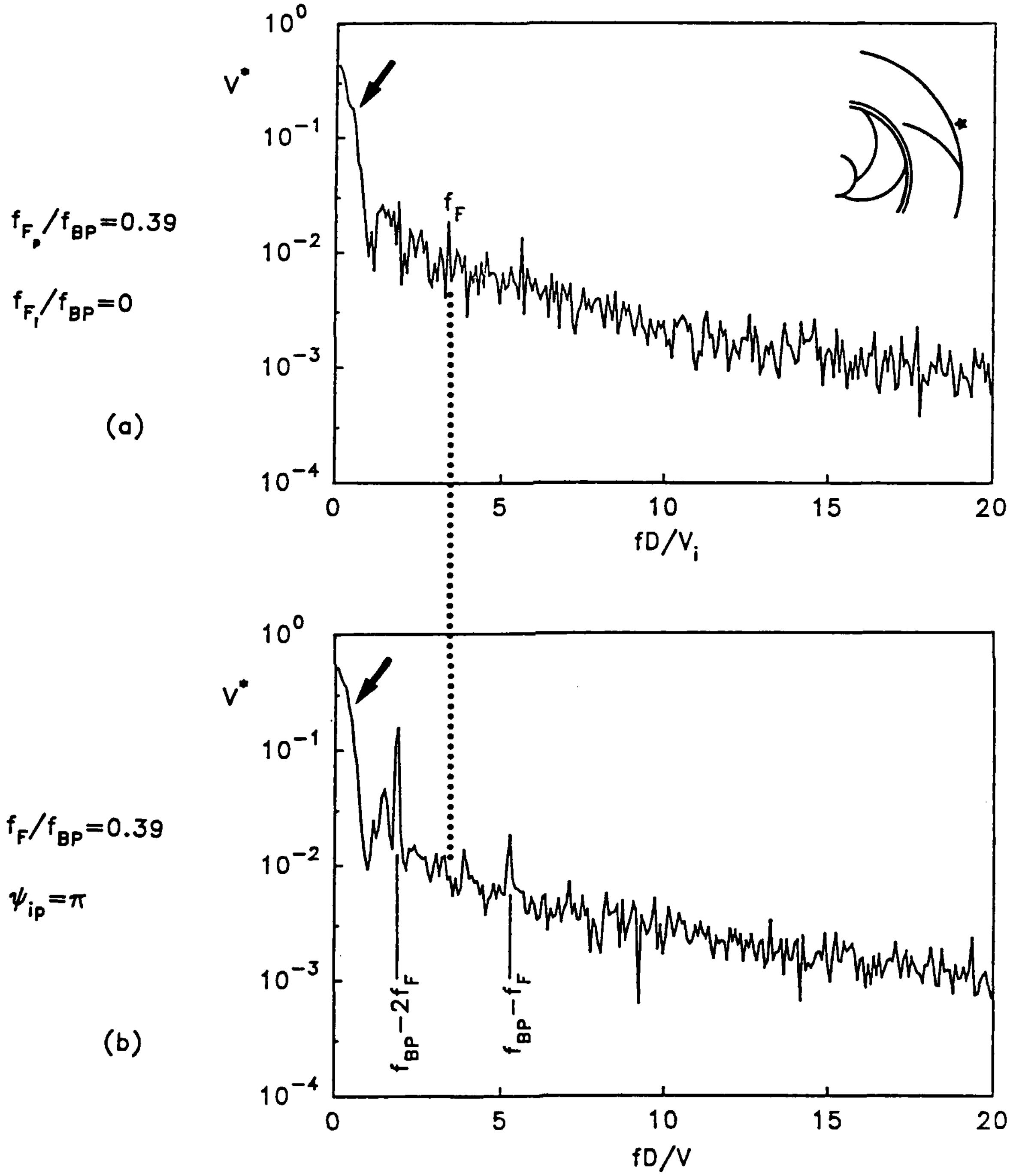
The power spectral density V^* of the velocity fluctuation is measured at the indicated (∗) location between the discharge of the impeller and the leading-edge of the diffuser blade for an off-design flow coefficient $\Phi = 0.188$. In the top plot, no perturbations are applied. In the middle plot, there is excitation only of the inflow at frequency f_{F_p} relative to the blade passing frequency f_{BP} of $f_{F_p}/f_{BP} = 0.67$. In the bottom plot, there is simultaneous excitation of the inflow velocity and the tangential velocity of the impeller at a dimensionless frequency $f_F/f_{BP} = 0.67$, and with the phase angle between the perturbations of the $\psi_{ip} = \pi$.

EFFECTS OF CONTROLLED EXCITATION IN PRESENCE OF DIFFUSER BLADE: EFFECTS OF INFLOW AND IMPELLER PERTURBATIONS



The power spectral density V^* of the velocity fluctuation is measured at the indicated (*) location between the discharge of the impeller and the leading-edge of the diffuser blade for an off-design flow coefficient $\Phi = 0.071$. In the top plot, no perturbations are applied. In the middle plot, there is excitation only of the inflow at frequency f_{F_p} relative to the blade passing frequency f_{BP} of $f_{F_p}/f_{BP} = 0.25$. In the bottom plot, there is simultaneous excitation of the inflow velocity and tangential velocity of the impeller at a dimensionless frequency $f_F/f_{BP} = 0.67$, with a phase angle between the perturbations of $\psi_{ip} = \pi$.

EFFECTS OF CONTROLLED EXCITATION IN PRESENCE OF DIFFUSER BLADE: EFFECTS OF INFLOW AND IMPELLER PERTURBATIONS



The power spectral density V^* of velocity fluctuation is measured at the exit of the diffuser in presence of a stationary diffuser blade. In the top plot, perturbations of the inflow at frequency f_{F_P} relative to the blade passing frequency f_{BP} of f_{F_P}/f_{BP} = 0.39 are applied. In the bottom plot, the same excitation condition holds for both the inflow and tangential velocity of the impeller, with the phase angle $\psi_{ip} = \pi$ between them. Note the large amplitude of the low frequency fluctuations generated in both cases. Different discrete components are evident at this location, depending upon the condition of excitation with or without perturbation of the impeller.

OVERALL RESPONSE TO CONTROLLED EXCITATION: SUMMARY

I. POSSIBLE TYPES OF RESPONSE DUE TO OSCILLATIONS OF INFLOW AT FREQUENCY f_F

- GENERATION OF LARGE NUMBER OF DISCRETE COMPONENTS AT $nf_F \pm mf_{BP}$
- ATTENUATION OF DISCRETE COMPONENTS AT f_F AND f_{BP}
- ALTERATION OF LOW FREQUENCY, BROADBAND CONTRIBUTIONS

II. POSSIBLE TYPES OF RESPONSE DUE TO SIMULTANEOUS OSCILLATIONS OF INFLOW AND IMPELLER AT FREQUENCY f_F

- GENERATION OF LARGE NUMBER OF DISCRETE COMPONENTS AT $nf_F \pm mf_{BP}$ EVEN AT LOW f_F
- ENHANCEMENT OR ATTENUATION OF COMPONENT f_F; ATTENUATION OF COMPONENT AT f_{BP}

III. POSSIBLE IMPLICATIONS OF FOREGOING DISCRETE RESPONSE FOR LOW FREQUENCY, BROADBAND RESPONSE

- LOCAL ALTERATIONS OF LOW FREQUENCY BROADBAND RESPONSE
- INITIAL CONDITIONS FOR SPATIAL DELAY OF DISCRETE COMPONENTS TO BROADBAND FLUCTUATIONS IN VANELESS DIFFUSER
- INITIAL CONDITIONS FOR LOW FREQUENCY STALL FLUCTUATIONS ALONG DIFFUSER BLADE

UNSTEADY FLOW DISTORTION PAST BLADES

- **OBJECTIVES**
- **RESEARCH PLAN**
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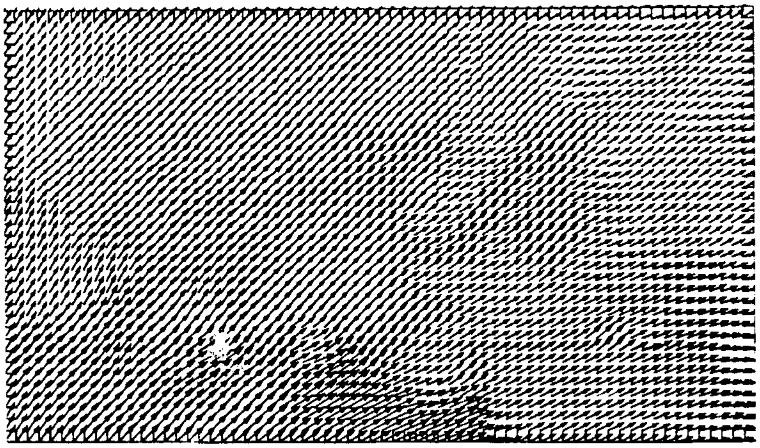
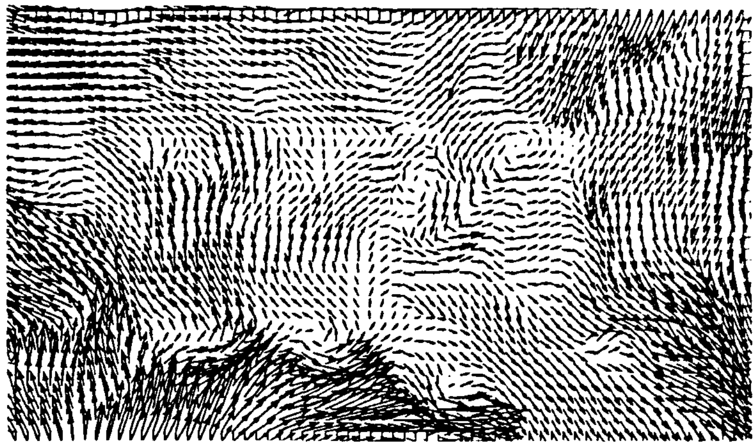
  - √ THREE-DIMENSIONAL NATURE OF FLOW STRUCTURE

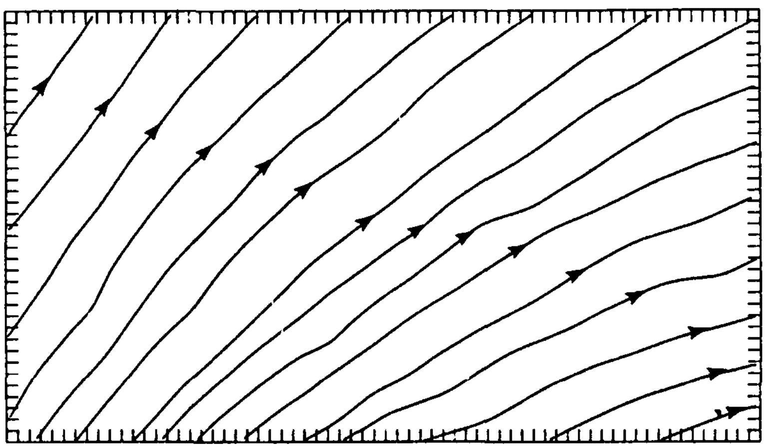
FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER



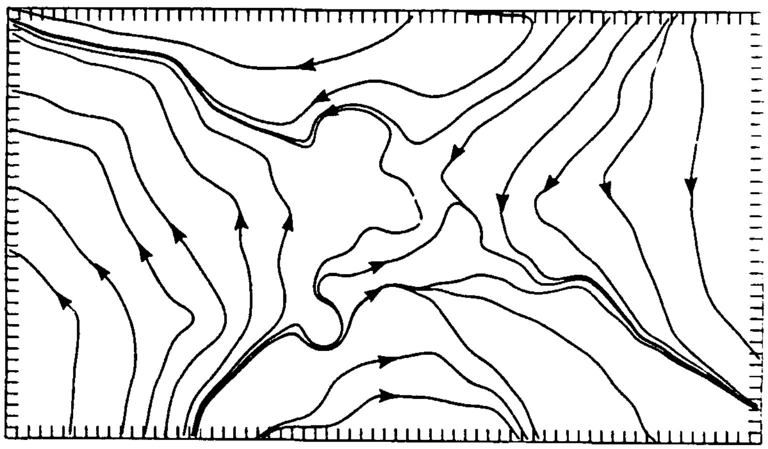
VELOCITY FIELD IN LABORATORY REFERENCE FRAME



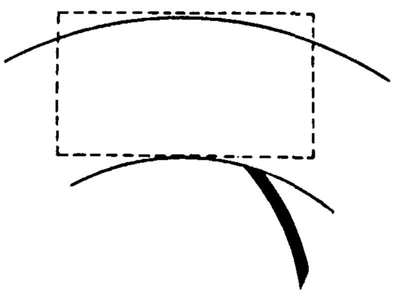
VELOCITY FIELD IN BIASED FRAME



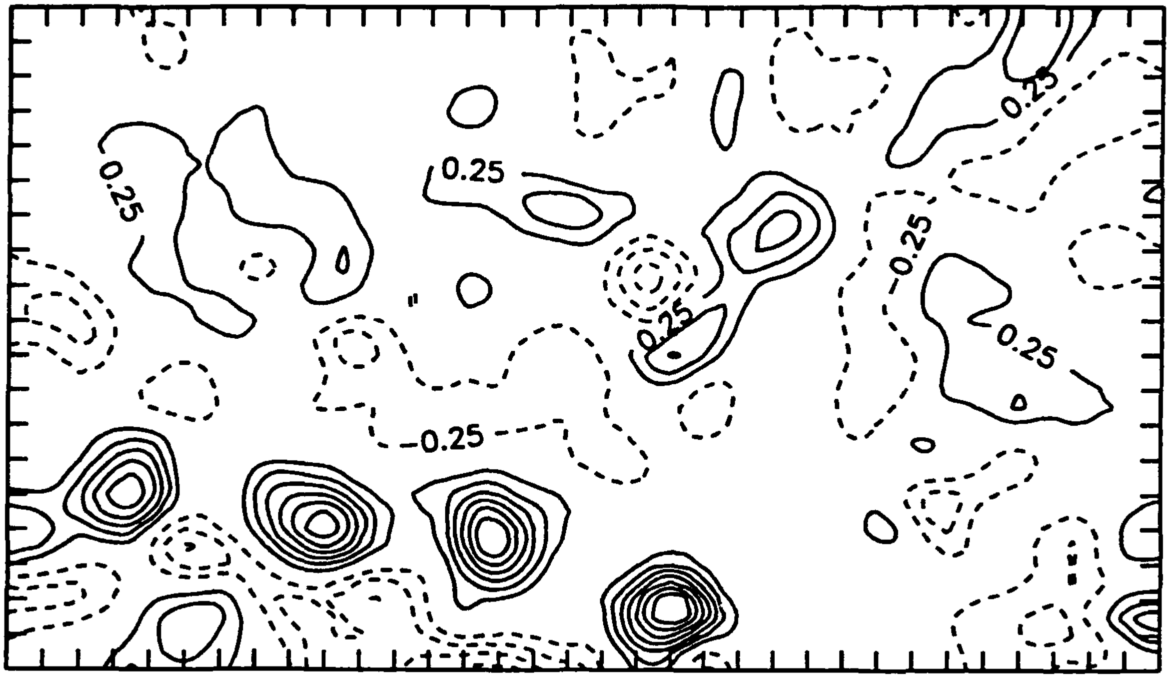
STREAMLINE PATTERN IN LABORATORY FRAME



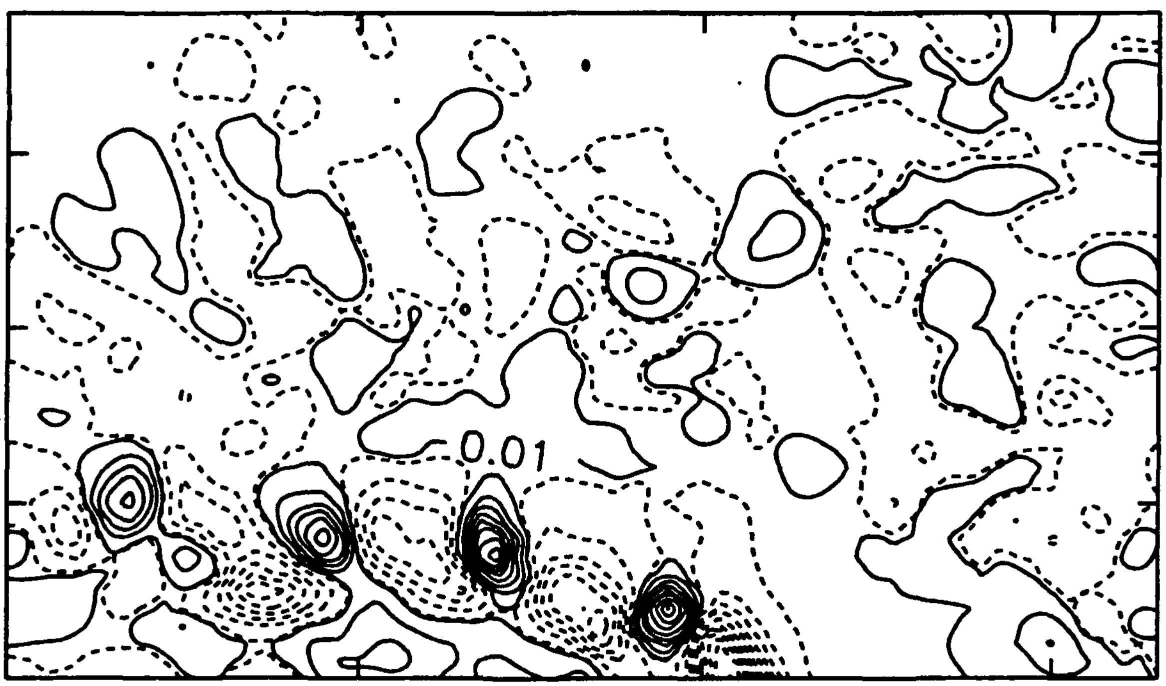
STREAMLINE PATTERN IN BIASED FRAME



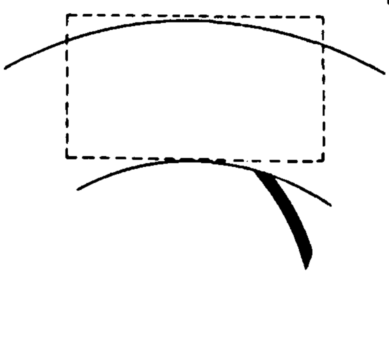
FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER



INSTANTANEOUS VORTICITY $\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$

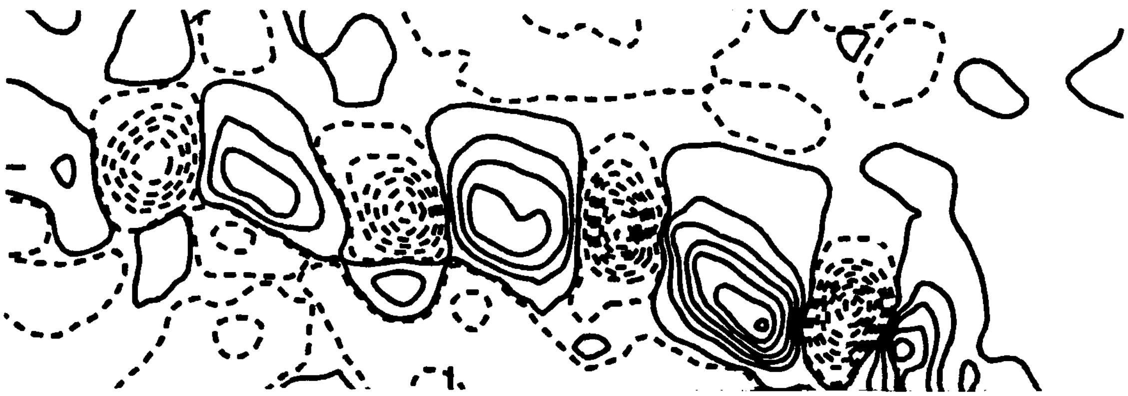


INSTANTANEOUS PRESSURE SOURCE TERM $\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right)$

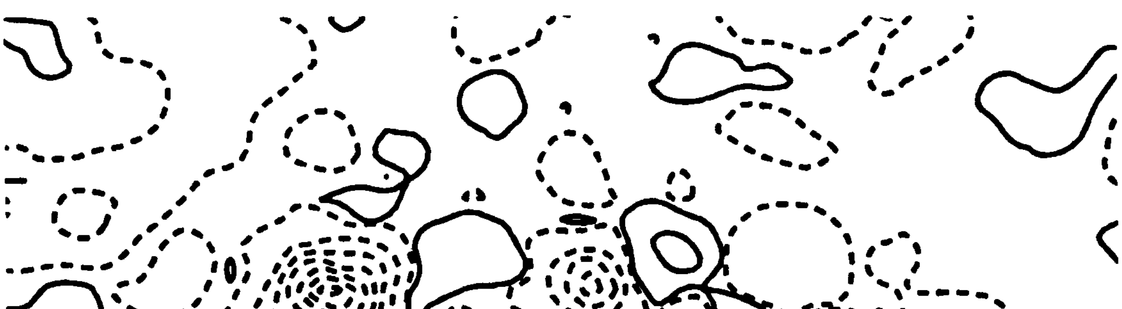


FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER

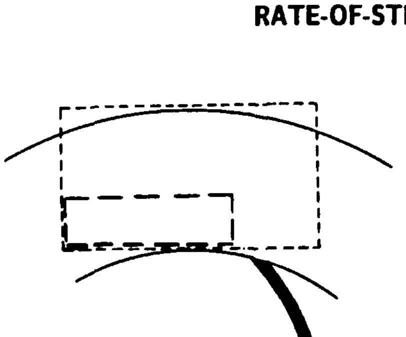
TOTAL INSTANTANEOUS SOURCE $\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right)$



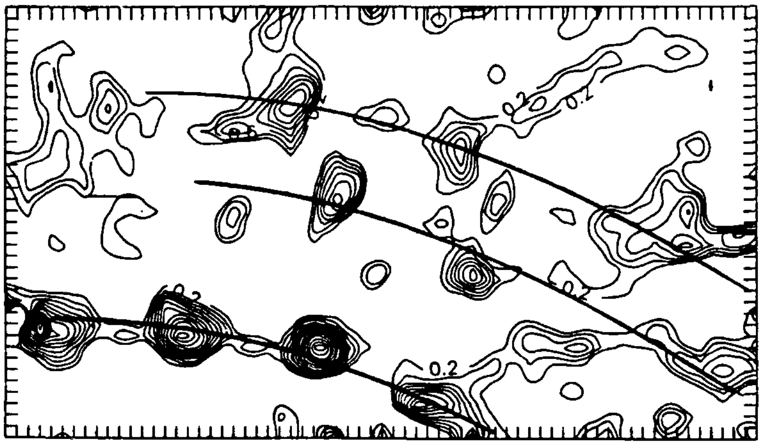
VORTICITY-RELATED SOURCE $\left(\frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right)$



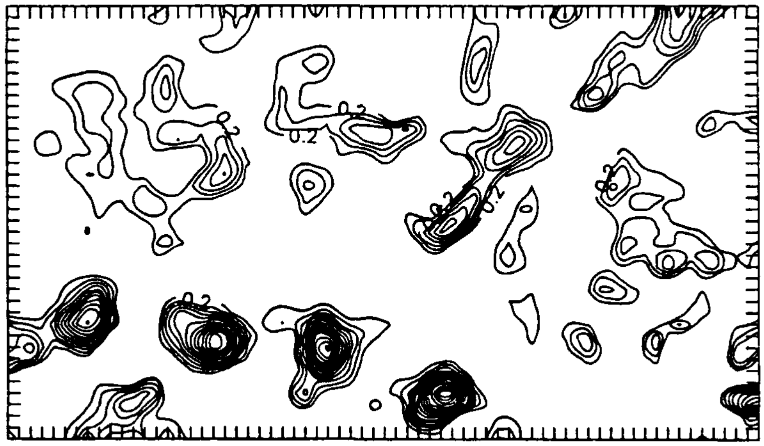
RATE-OF-STRAIN-RELATED SOURCE $\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y}\right)$



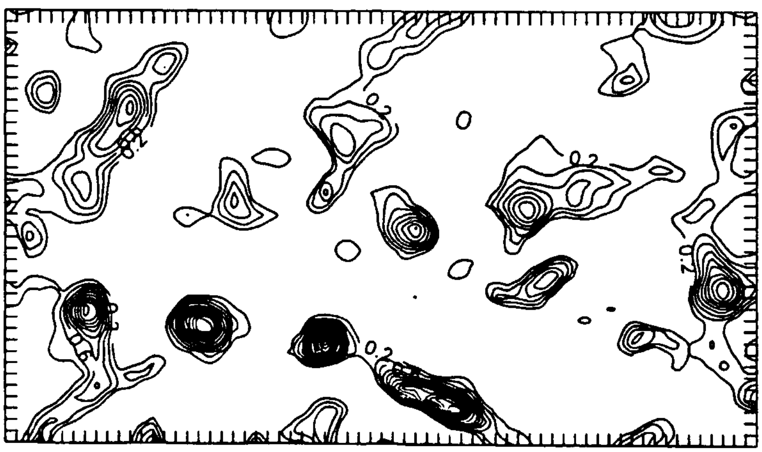
FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER



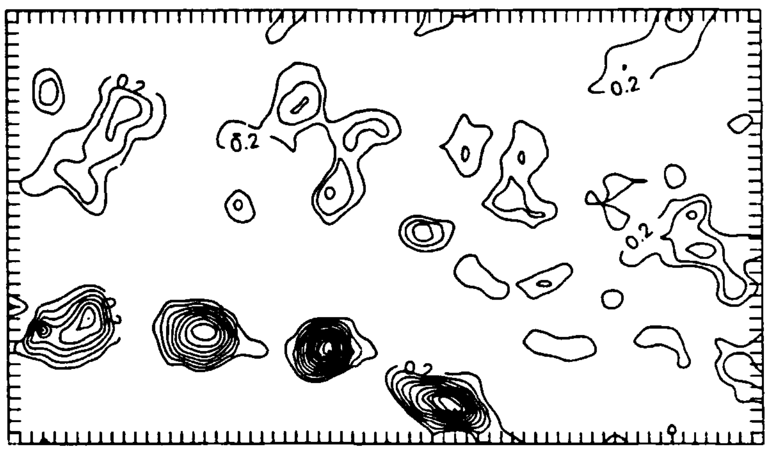
INSTANTANEOUS (POSITIVE) VORTICITY:
REALIZATION #1



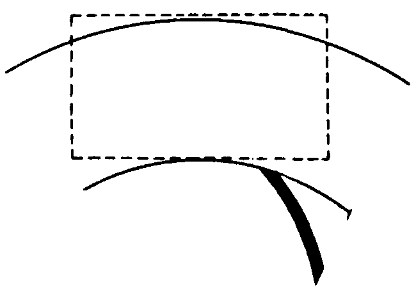
INSTANTANEOUS (POSITIVE) VORTICITY:
REALIZATION #2



INSTANTANEOUS (POSITIVE) VORTICITY:
REALIZATION #3



AVERAGE OF THREE REALIZATIONS OF
INSTANTANEOUS (POSITIVE) VORTICITY



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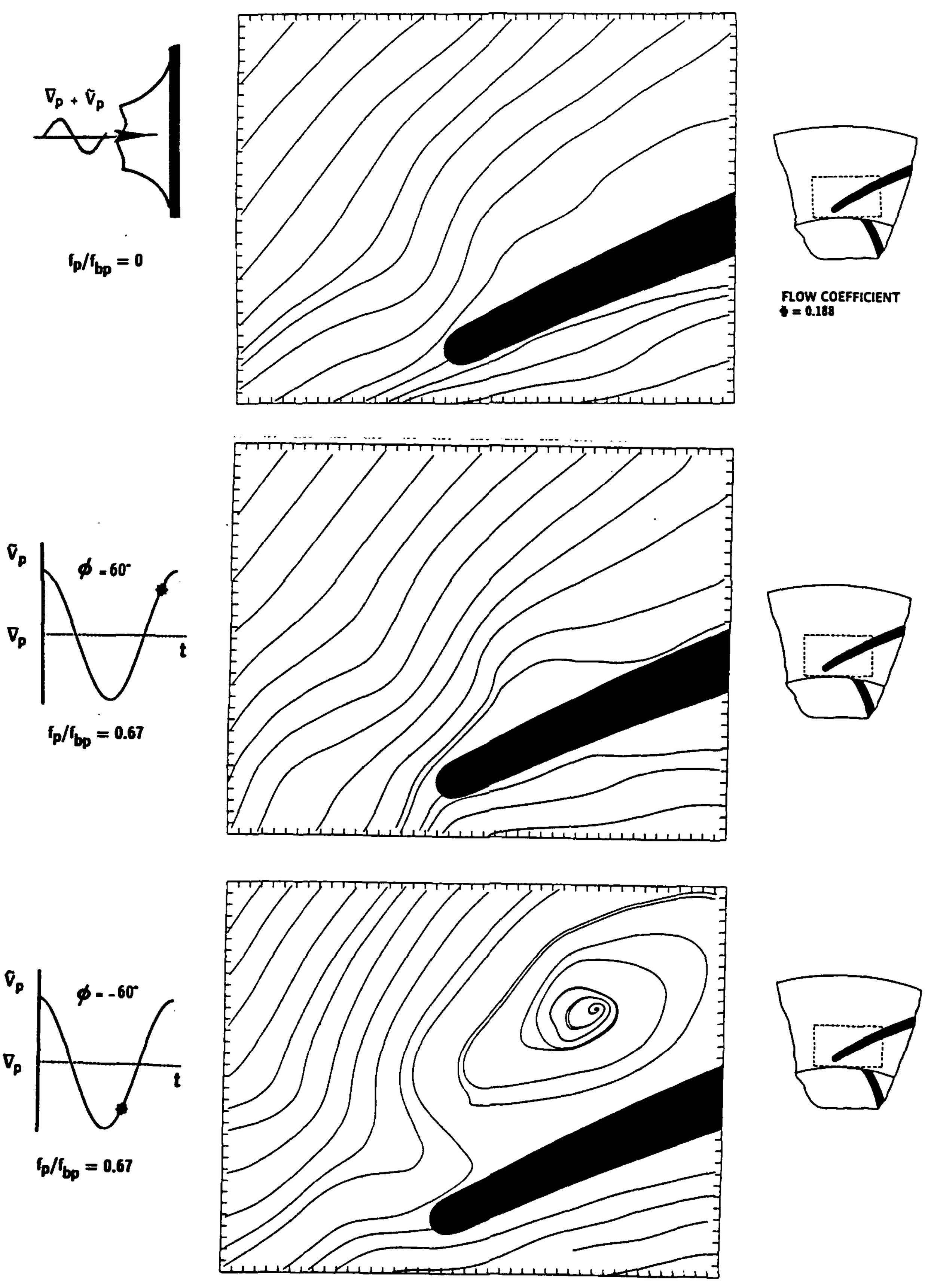
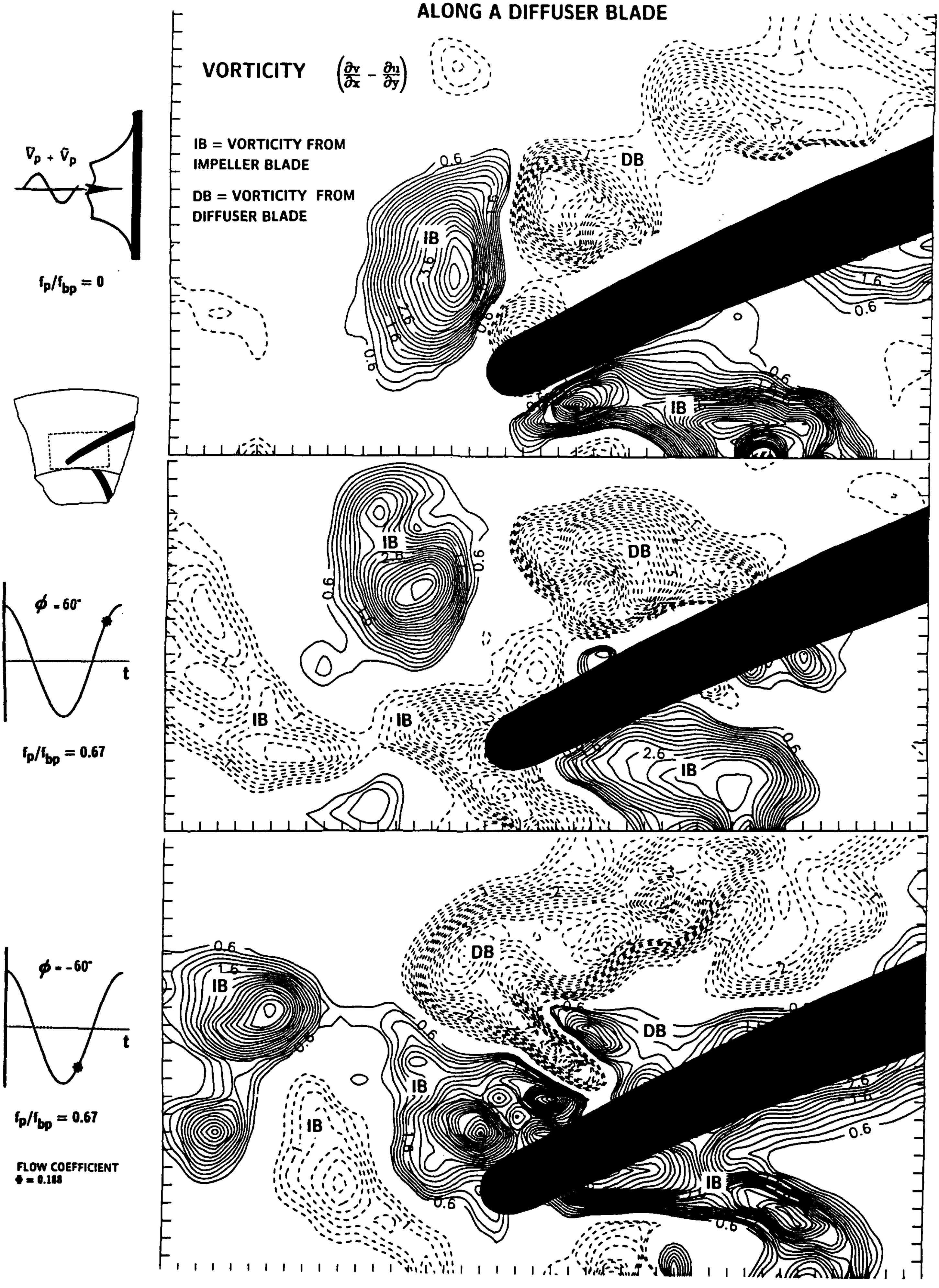
FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

STREAMLINES IN LABORATORY REFERENCE FRAME

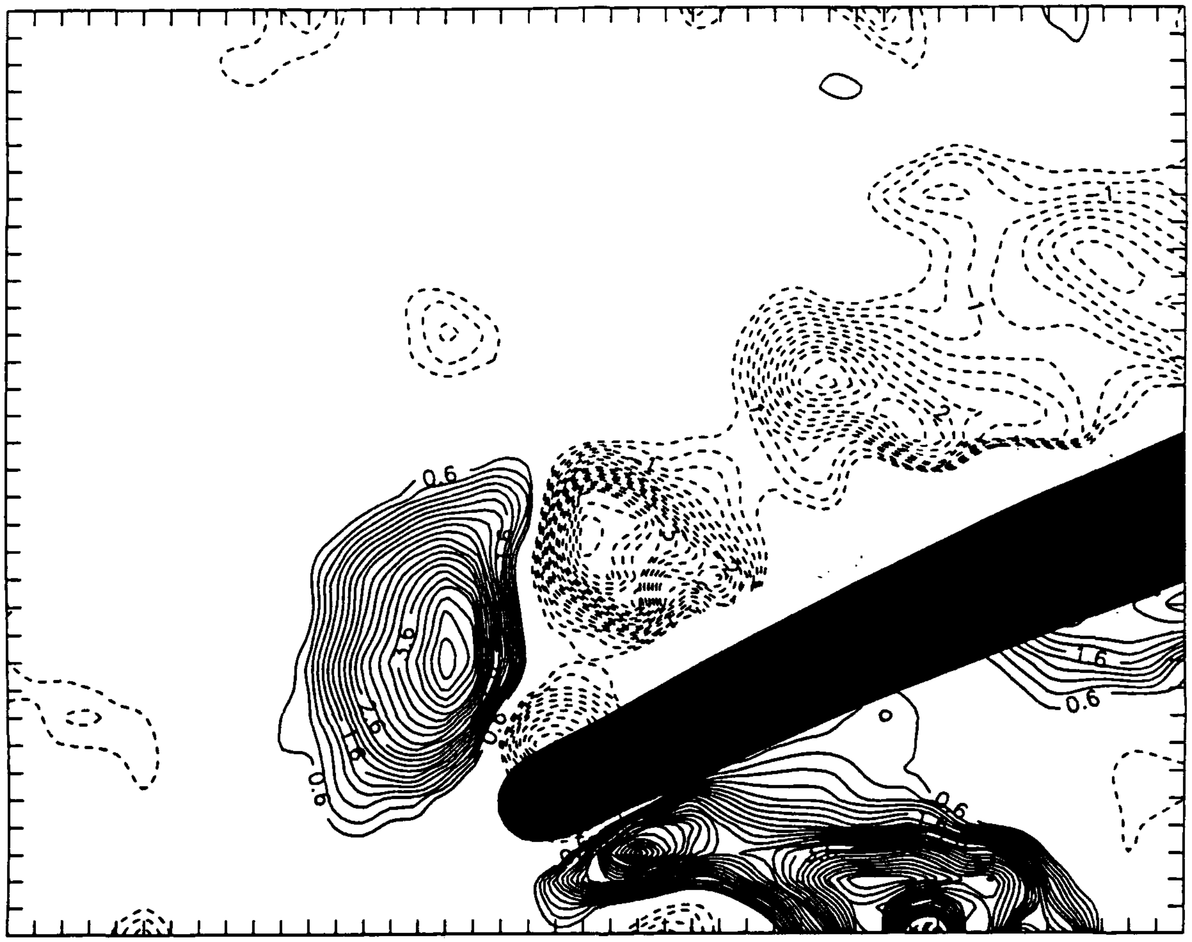


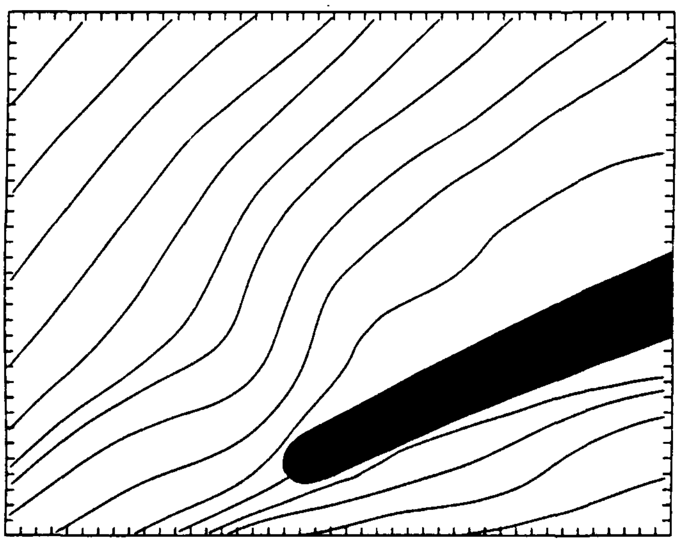
FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

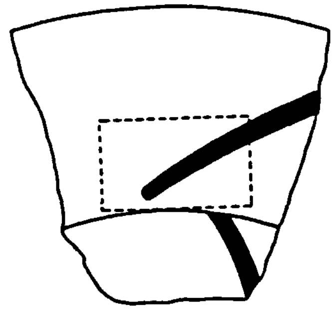


FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

VORTICITY





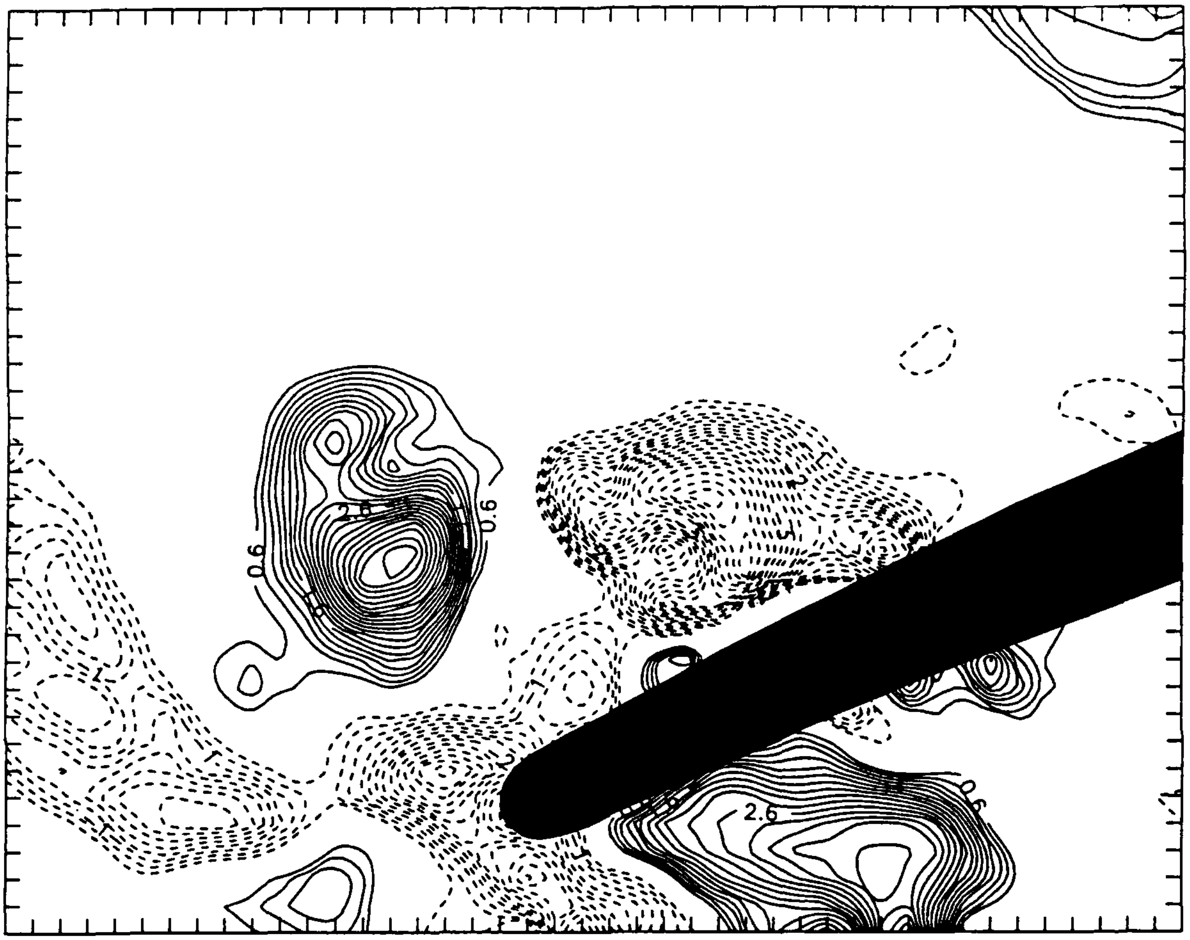


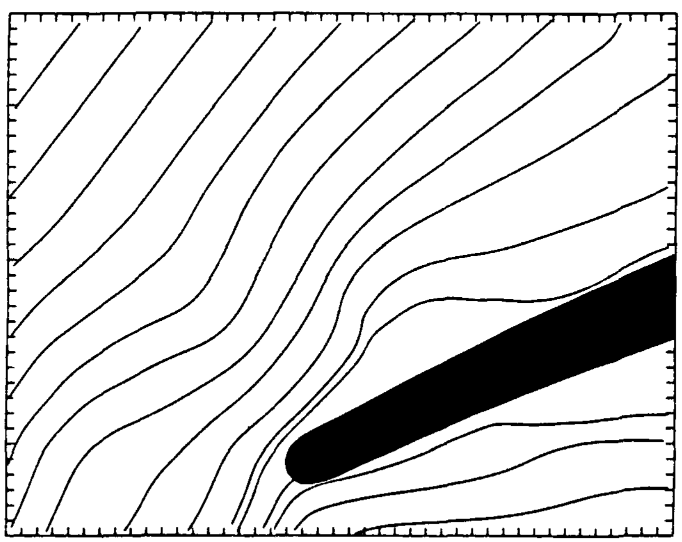
$f_p/f_{bp} = 0$

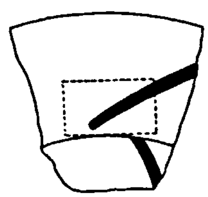
FLOW COEFFICIENT
$\Phi = 0.188$

FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

VORTICITY

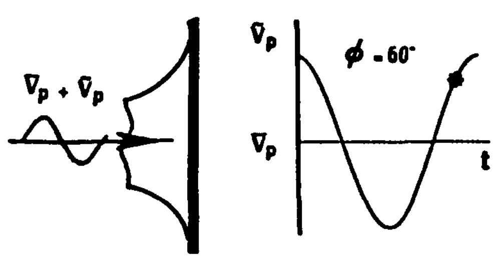






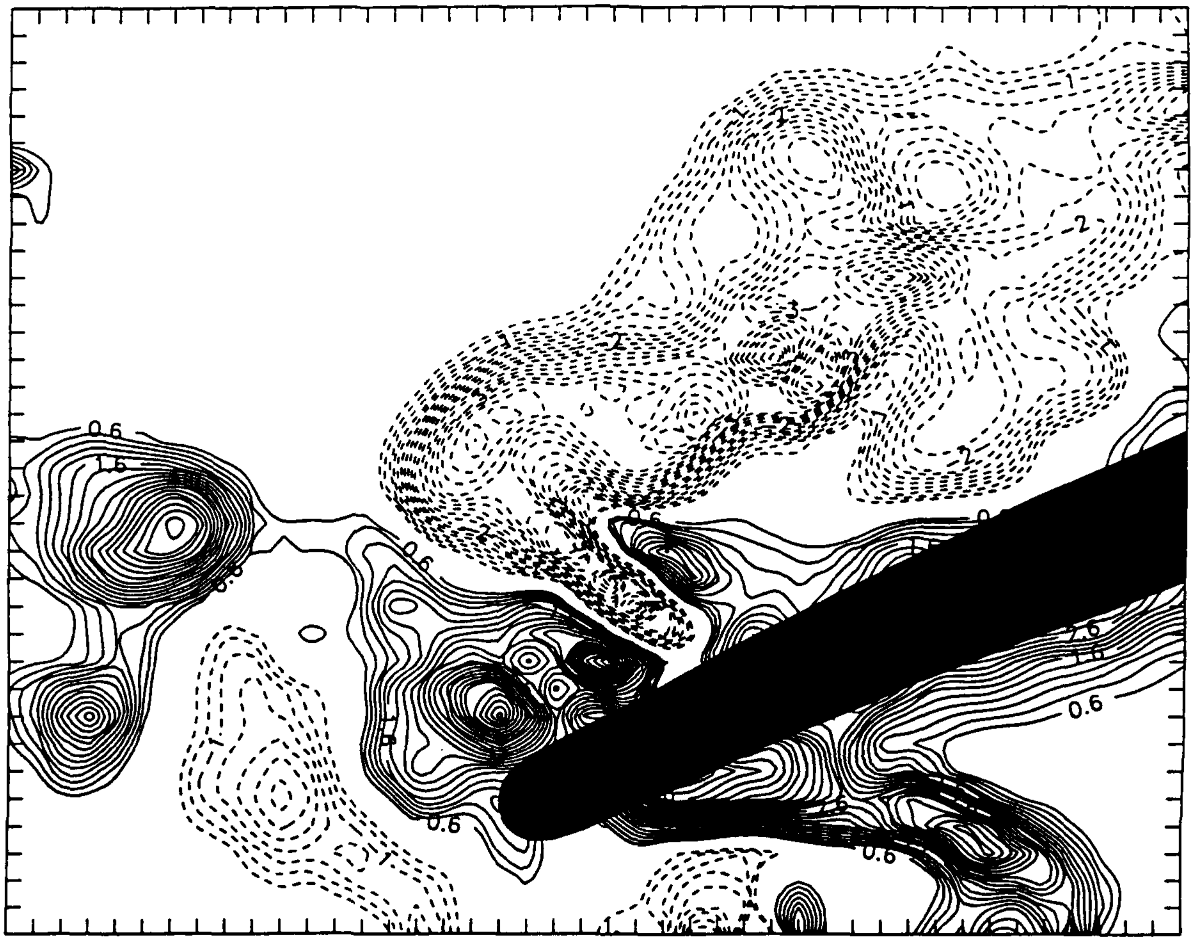
$f_p/f_{bp} = 0.67$

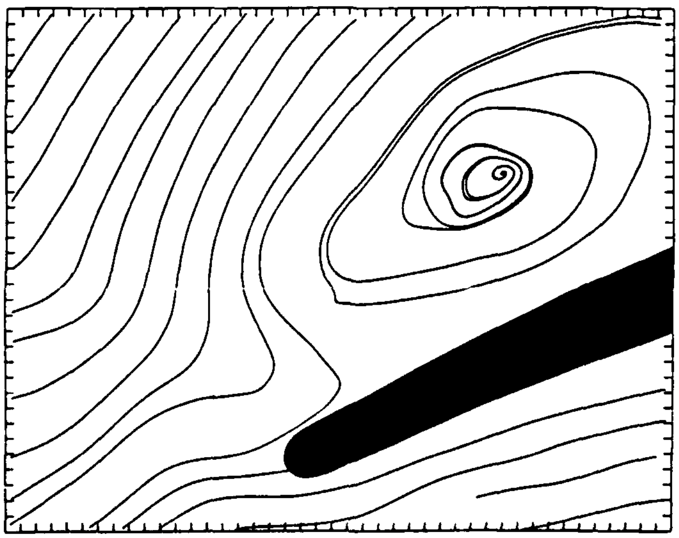
FLOW COEFFICIENT
$\Phi = 0.188$

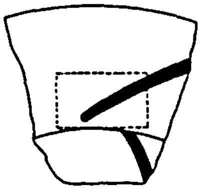


FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

VORTICITY

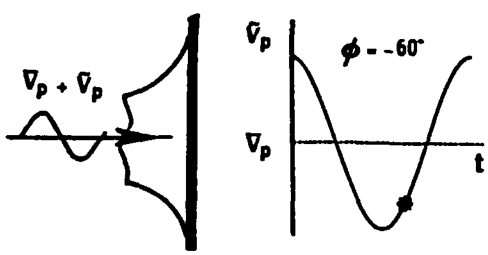




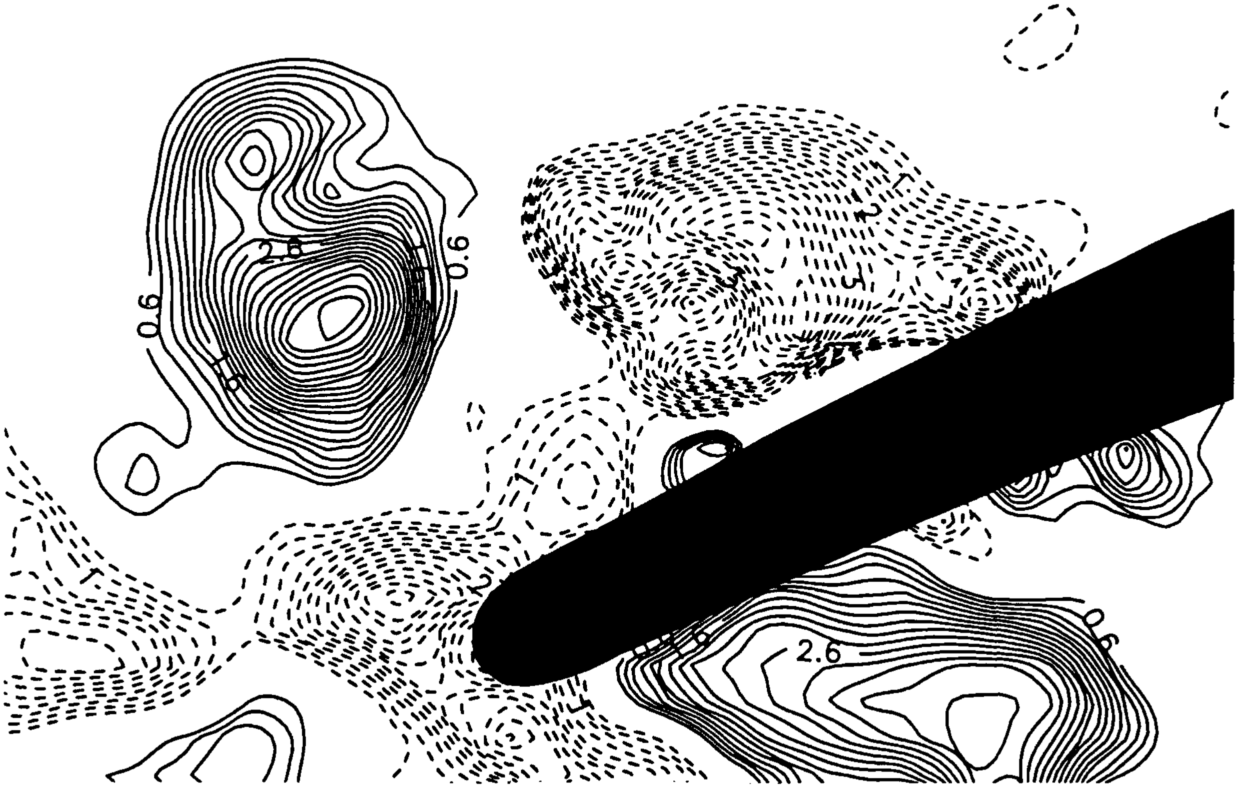


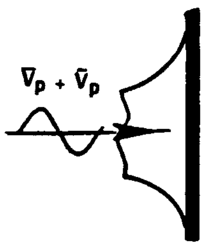
$f_p/f_{bp} = 0.67$

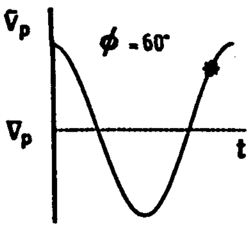
FLOW COEFFICIENT
$\Phi = 0.148$



FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

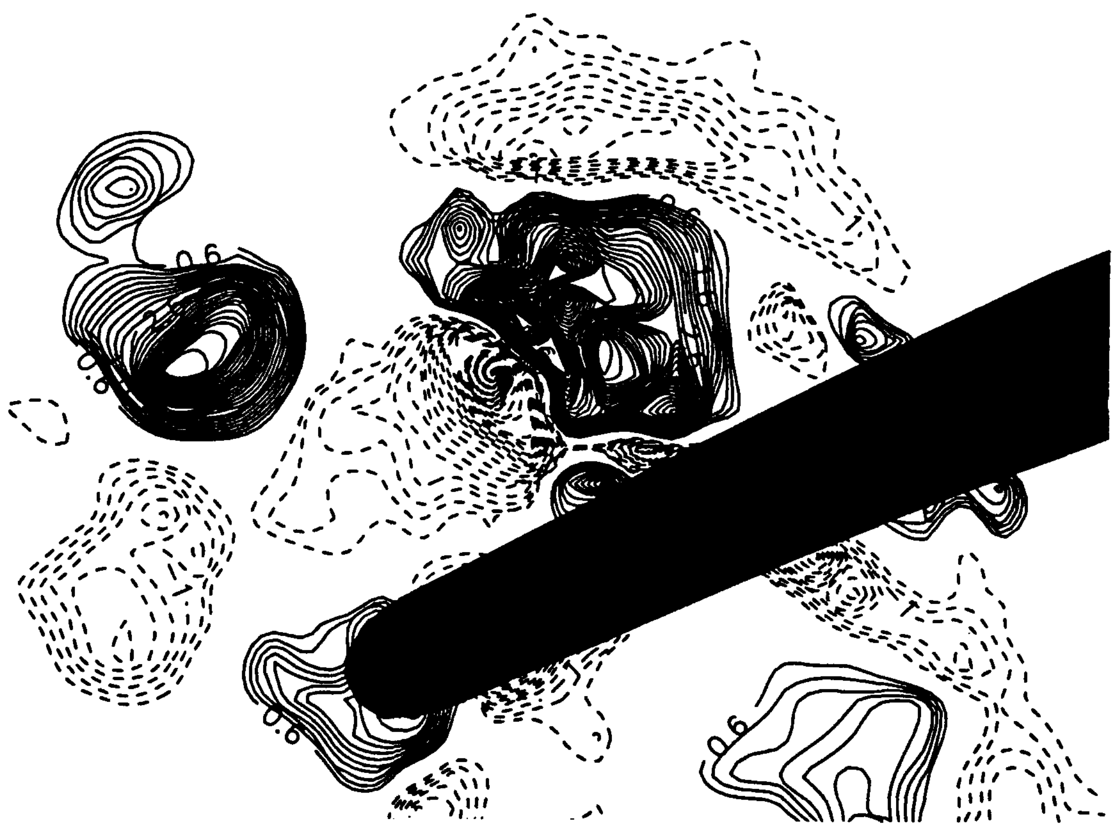






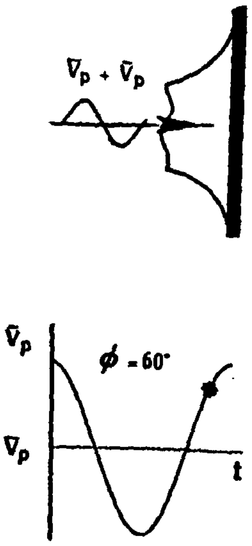
$f_p/f_{bp} = 0.67$

INSTANTANEOUS VORTICITY $\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$

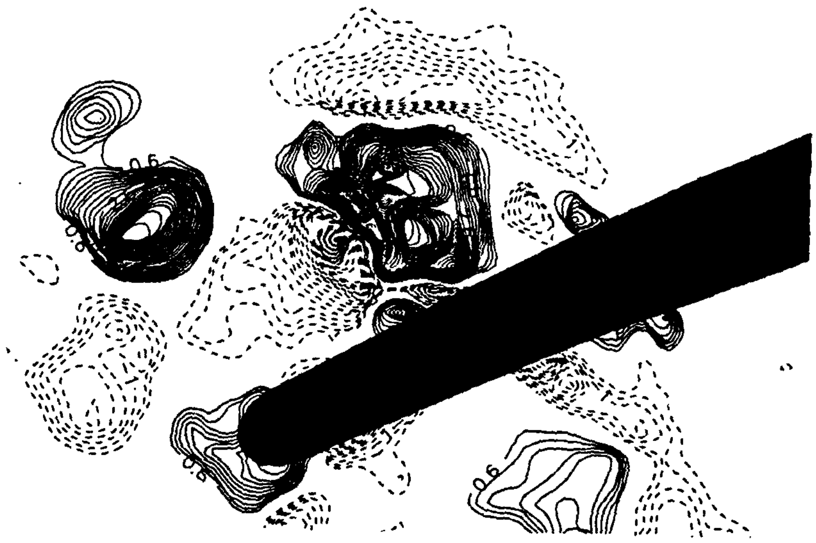


INSTANTANEOUS PRESSURE SOURCE $\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right)$

FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

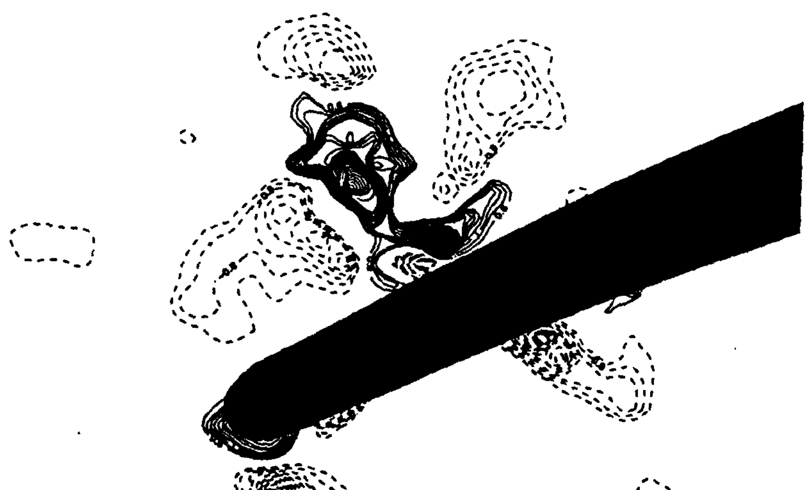


$f_p/f_{bp} = 0.67$



TOTAL INSTANTANEOUS SOURCE $\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right)$

VORTICITY-RELATED SOURCE $\left(\frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right)$



RATE-OF-STRAIN-RELATED SOURCE $\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y}\right)$

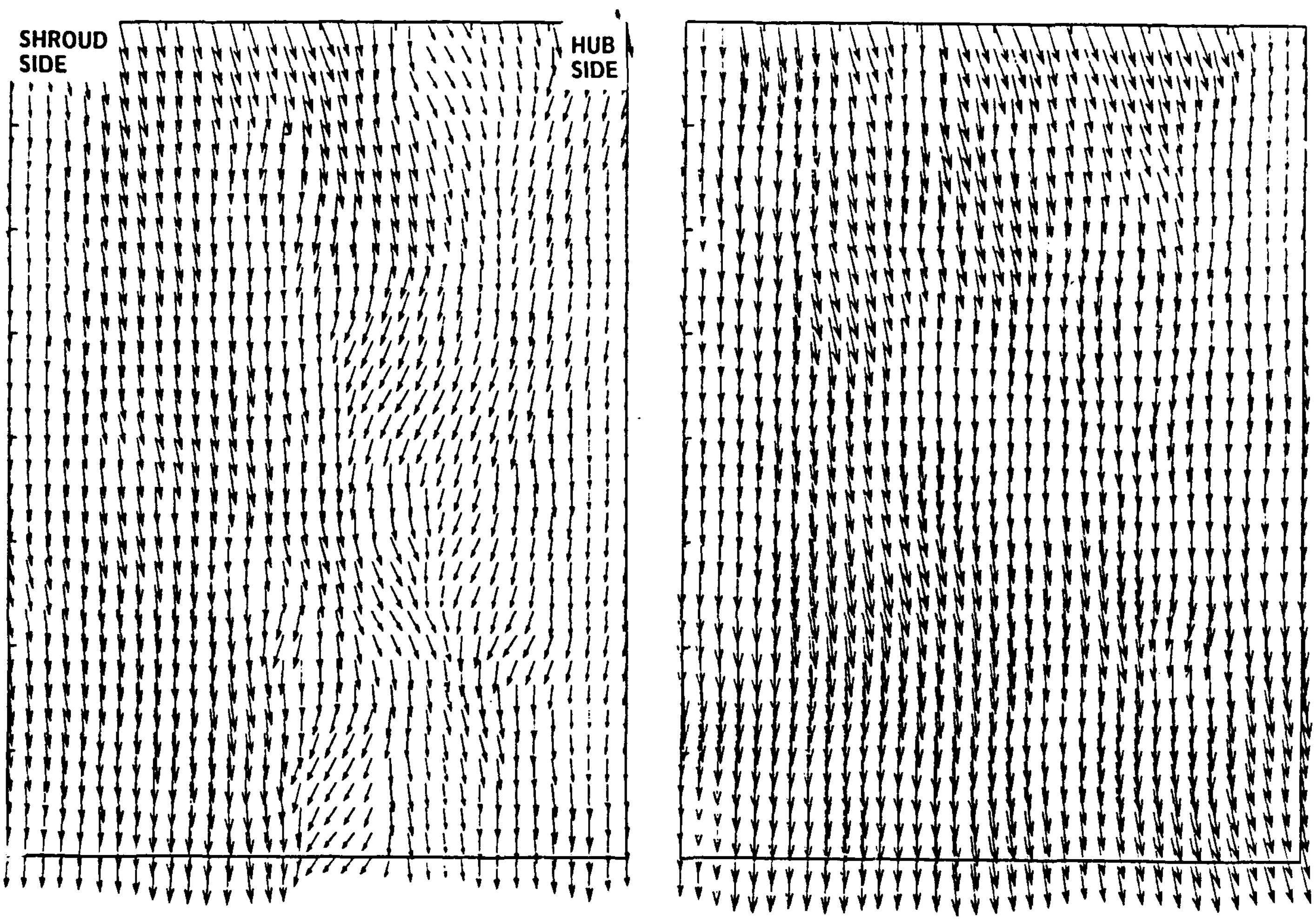
UNSTEADY FLOW DISTORTION PAST BLADES

- OBJECTIVES
- RESEARCH PLAN
- PRINCIPAL PHYSICAL AND THEORETICAL CONCEPTS
- EXPERIMENTAL TECHNIQUES
- GENERIC CLASSES OF EDGE/SURFACE INTERACTION
  - √ LEADING-EDGE
  - √ TRAILING-EDGE
  - √ LEADING-/TRAILING-EDGE
- EXPERIMENTAL SYSTEMS
  - √ GENERIC SYSTEMS FOR LEADING- AND TRAILING-EDGE INTERACTIONS
  - √ ACTIVELY-CONTROLLED PUMPING SYSTEM
- FLOW STRUCTURE IN ACTIVELY-CONTROLLED RADIAL-FLOW MACHINE
  - √ OVERALL SYSTEM RESPONSE
  - √ FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER
  - √ FLOW STRUCTURE AND PRESSURE SOURCES ALONG DIFFUSER BLADE OR CUTOFF
  - √ FLOW STRUCTURE AND PRESSURE SOURCES AT TRAILING-EDGE OF IMPELLER BLADE
  - √ THREE-DIMENSIONAL NATURE OF FLOW STRUCTURE

UNSTEADY FLOW DISTORTION PAST BLADES

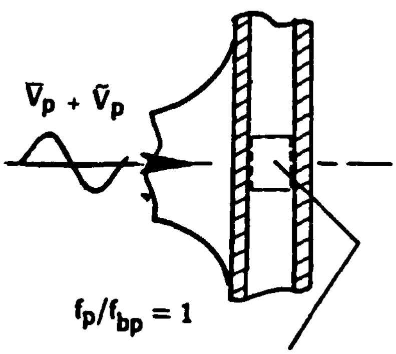
- OBJECTIVES
- RESEARCH PLAN
- PRINCIPAL PHYSICAL AND THEORETICAL CONCEPTS
- EXPERIMENTAL TECHNIQUES
- GENERIC CLASSES OF EDGE/SURFACE INTERACTION
  - √ LEADING-EDGE
  - √ TRAILING-EDGE
  - √ LEADING-/TRAILING-EDGE
- EXPERIMENTAL SYSTEMS
  - √ GENERIC SYSTEMS FOR LEADING- AND TRAILING-EDGE INTERACTIONS
  - √ ACTIVELY-CONTROLLED PUMPING SYSTEM
- FLOW STRUCTURE IN ACTIVELY-CONTROLLED RADIAL-FLOW MACHINE
  - √ OVERALL SYSTEM RESPONSE
  - √ FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER
  - √ FLOW STRUCTURE AND PRESSURE SOURCES ALONG DIFFUSER BLADE OR CUTOFF
  - √ FLOW STRUCTURE AND PRESSURE SOURCES AT TRAILING-EDGE OF IMPELLER BLADE
  - √ THREE-DIMENSIONAL NATURE OF FLOW STRUCTURE

FLOW THROUGH IMPELLER DIFFUSER SYSTEM: INSTANTANEOUS STRUCTURE IN CROSSFLOW PLANE



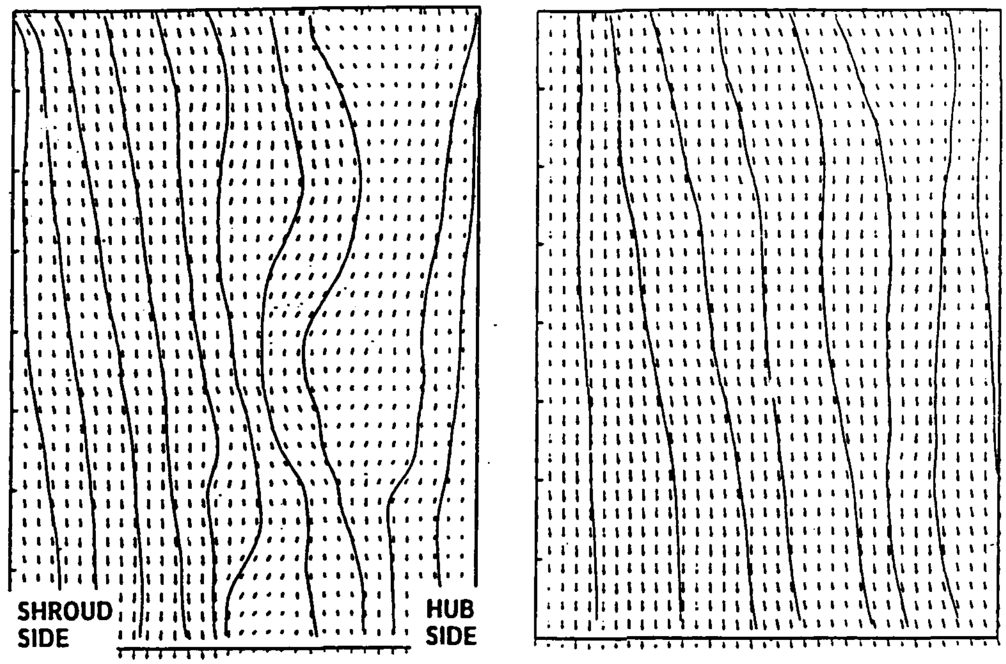
$t = 0$ $t = 2/f_{bp}$

INSTANTANEOUS VELOCITY
IN LABORATORY FRAME

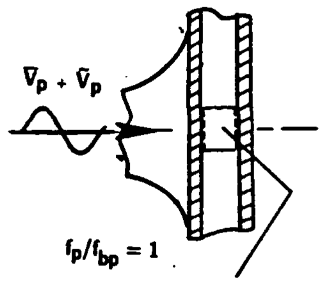


FIELD OF VIEW AT INLET
OF VANELESS DIFFUSER

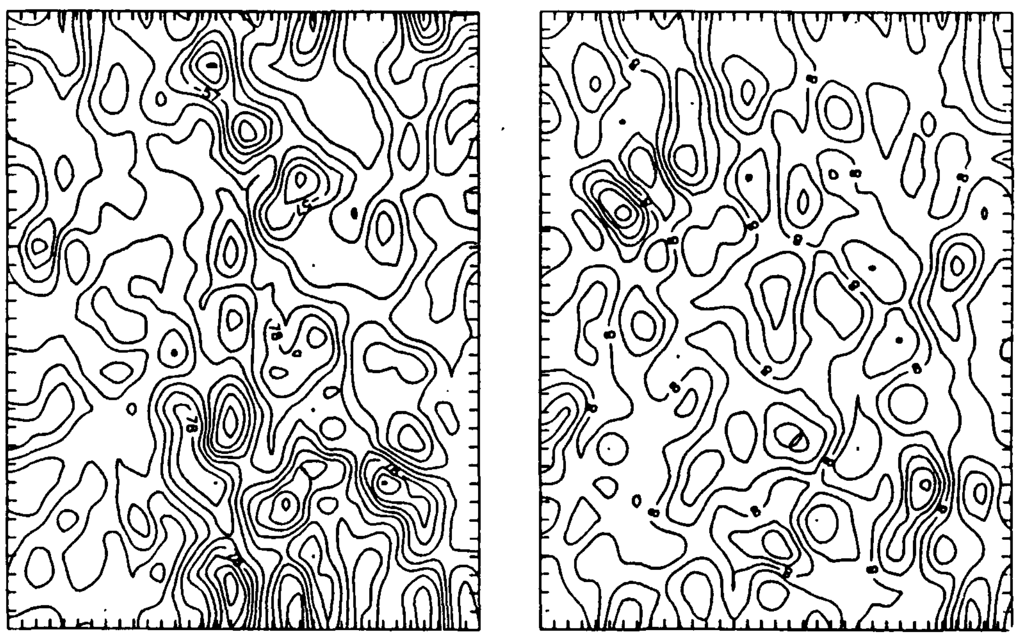
FLOW THROUGH IMPELLER DIFFUSER SYSTEM: INSTANTANEOUS STRUCTURE IN CROSSFLOW PLANE



t = 0 | INSTANTANEOUS STREAMLINES IN LABORATORY FRAME | t = $2/f_{bp}$

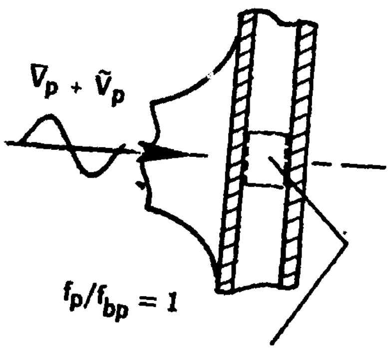


FIELD OF VIEW AT INLET OF VANELESS DIFFUSER

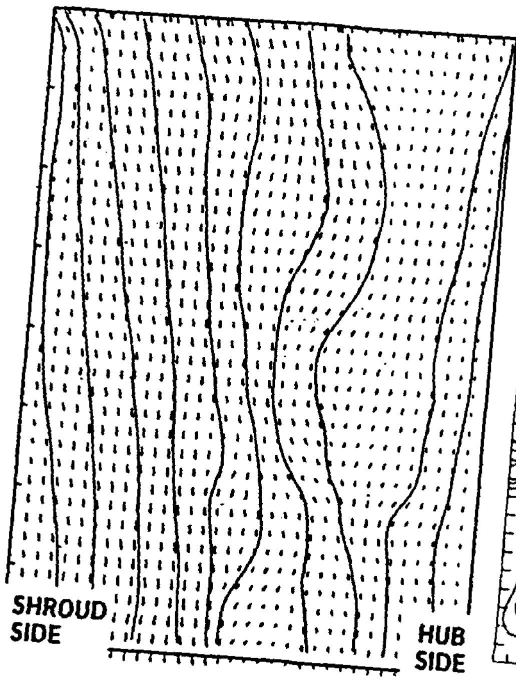


INSTANTANEOUS DISTRIBUTIONS OF STREAMWISE VORTICITY INCLUDING ENTIRE RANGE OF POSITIVE AND NEGATIVE CONTRIBUTIONS

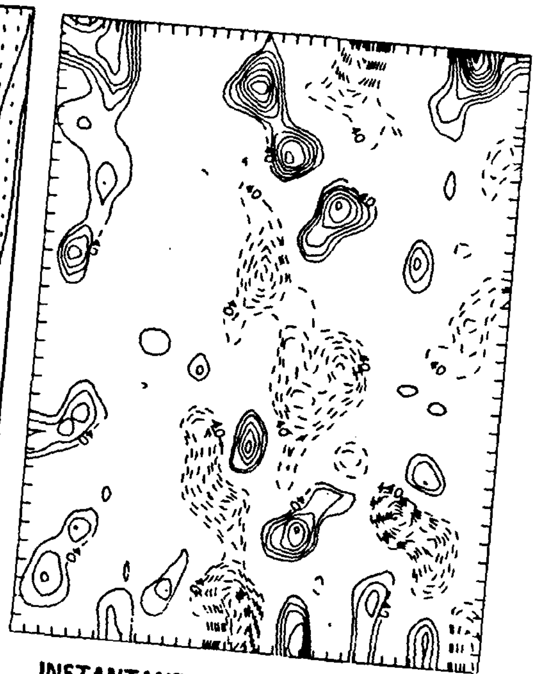
FLOW THROUGH IMPELLER DIFFUSER SYSTEM: INSTANTANEOUS STRUCTURE IN CROSSFLOW PLANE



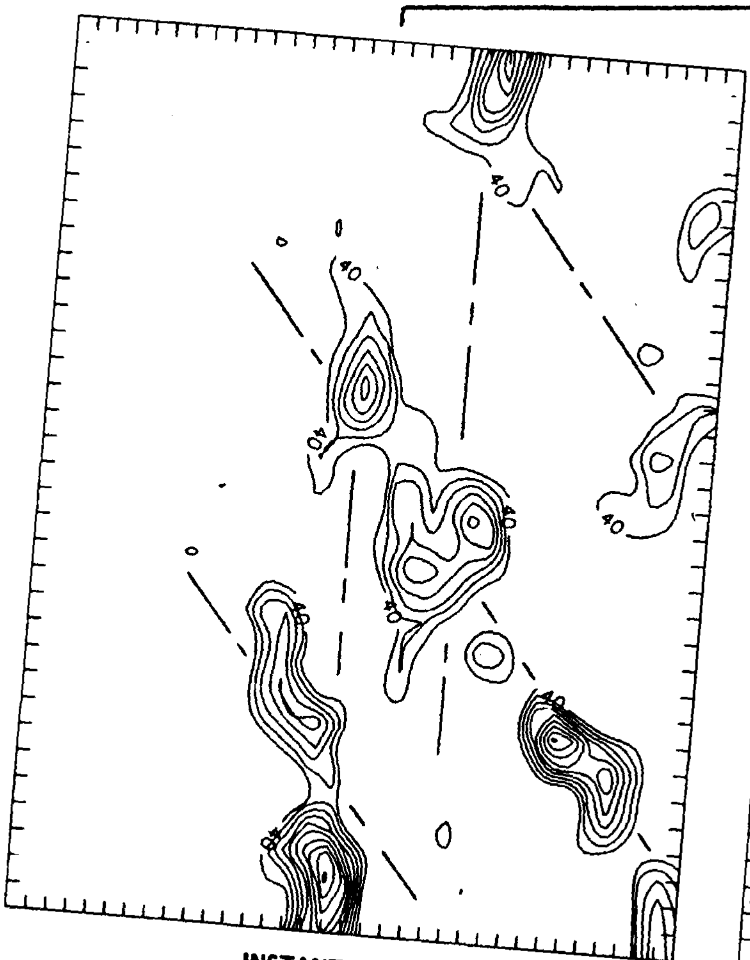
FIELD OF VIEW AT INLET OF VANELESS DIFFUSER



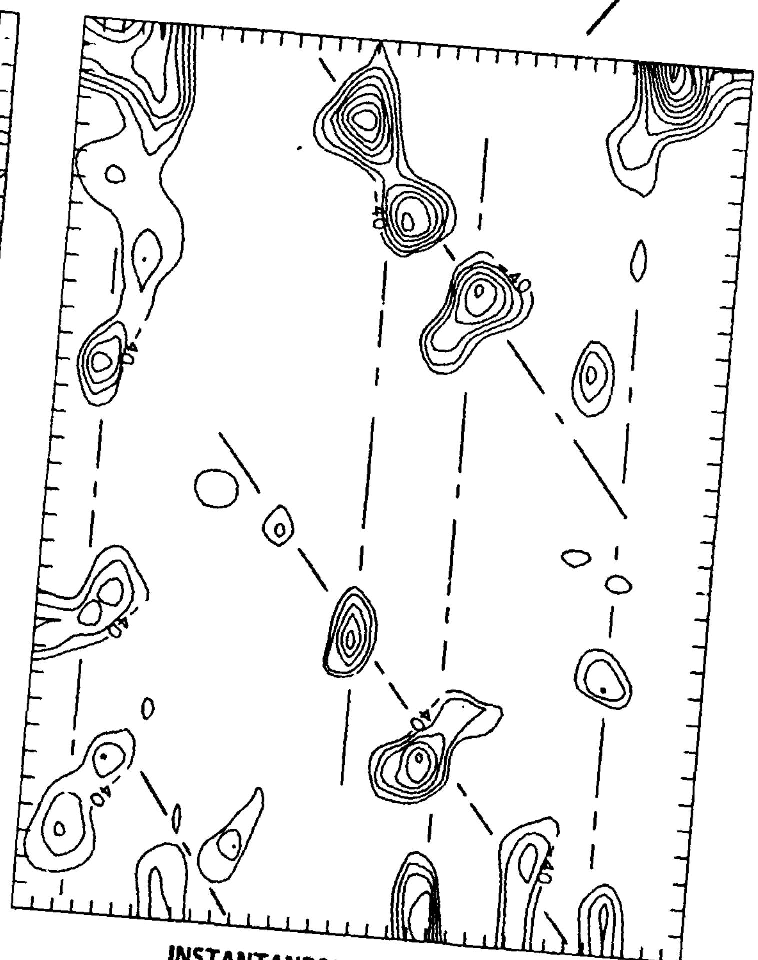
INSTANTANEOUS STREAMLINES IN LABORATORY FRAME



INSTANTANEOUS DISTRIBUTIONS OF STREAMWISE VORTICITY INCLUDING ENTIRE RANGE OF <u>POSITIVE</u> AND <u>NEGATIVE</u> CONTRIBUTIONS



INSTANTANEOUS NEGATIVE STREAMWISE VORTICITY



INSTANTANEOUS POSITIVE STREAMWISE VORTICITY